PARTON DISTRIBUTIONS
FOR LHC RUN II

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

LAL

ORSAY, JULY 3, 2015

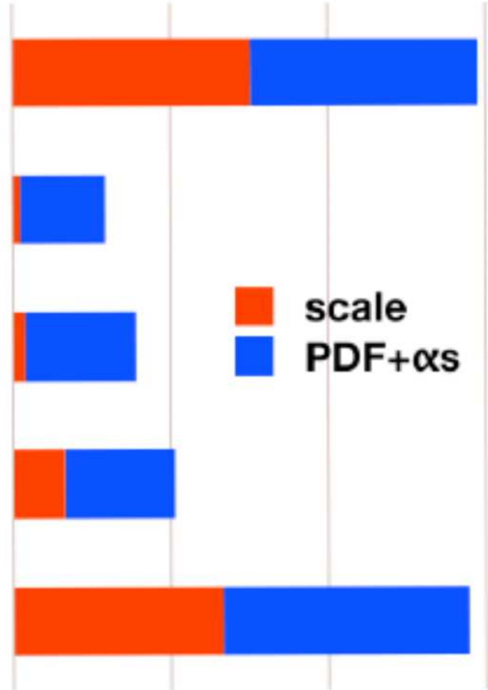
PROLOGUE

PDFs for LHC RUN I

WHY WORRY ABOUT PDFs?

Higgs production

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%

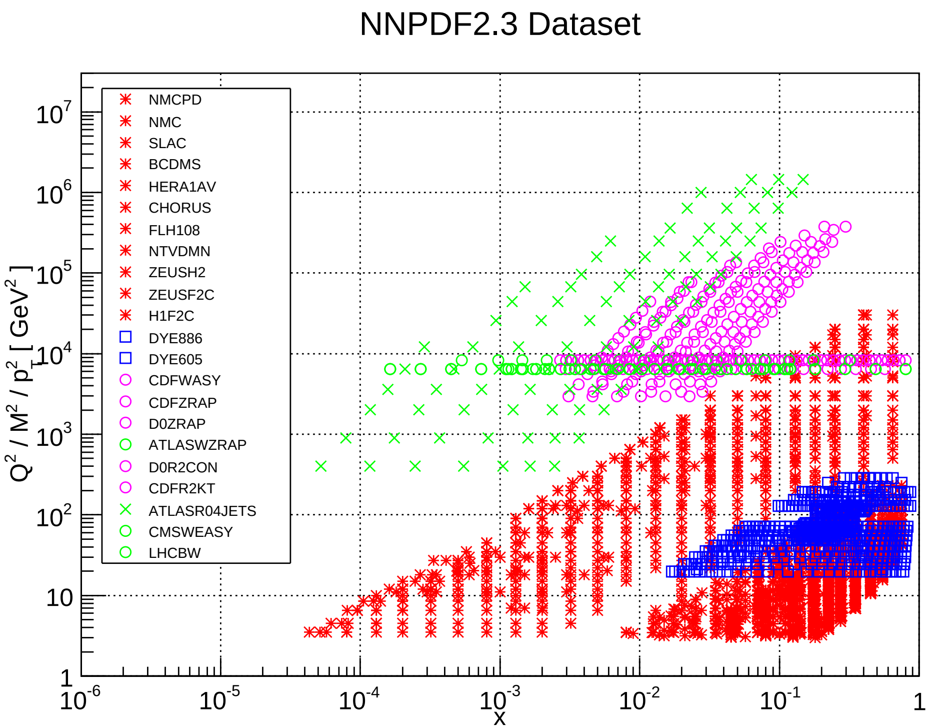


(J. Campbell, HCP2012)

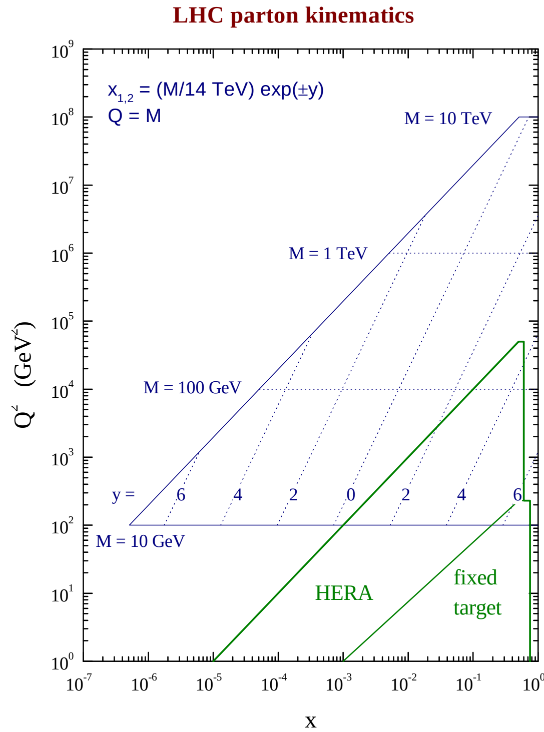
PDF UNCERTAINTY EITHER DOMINANT, OR VERY LARGE, OR BOTH
. . . AND NOT ONLY FOR THE HIGGS!
(W MASS DETERMINATION, NEW PHYSICS SEARCHES FOR HEAVY STATES,. . .)

PDFs for LHC Run I

$$\sigma_X(s, M_X^2) = \sum_{a,b} \int_{x_{\min}}^1 dx_1\, dx_2\, f_{a/h_1}(x_1) f_{b/h_2}(x_2) \hat{\sigma}_{q_a q_b \to X}\left(x_1 x_2 s, M_X^2\right)$$



LHC kinematics



	MSTW08	CT10	NNPDF2.3	HERAPDF1.5	ABM11/12	JR09
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✗	✔	✔
Fixed-target DY	✔	✔	✔	✗	✔	✔
Tevatron W+Z+jets	✔	✔	✔	✗	✗	✗
LHC W+Z+jets	✗	✗	✔	✗	some, approx.	✗

RUN I PDF SETS: THE APPROACH

METHODOLOGY

- STATISTICAL TREATMENT: CTEQ, MSTW HESSIAN WITH DYNAMICAL TOLERANCE; HERAPDF, STANDARD HESSIAN+PARM. ERROR ANALYSIS; GJR, HESSIAN WITH FIXED TOLERANCE; ABKM STANDARD HESSIAN; NNPDF MONTE CARLO (ALSO STUDIED BY HERAPDF, MSTW)
- PARTON PARAMETRIZATION: CTEQ, MSTW, HERAPDF $x^\alpha(1-x)^\beta \times$ POLYNOMIALS; GJR: DITTO + VALENCELIKE ASSUMPTION; NNPDF NEURAL NETS; CHEBYSHEV POLYNOMIALS STUDIED BY HERAPDF, MSTW;
- COVARIANCE MATRIX, NORMALIZATION UNCERTAINTIES, OUTLIERS, THEORETICAL UNCERTAINTIES ...

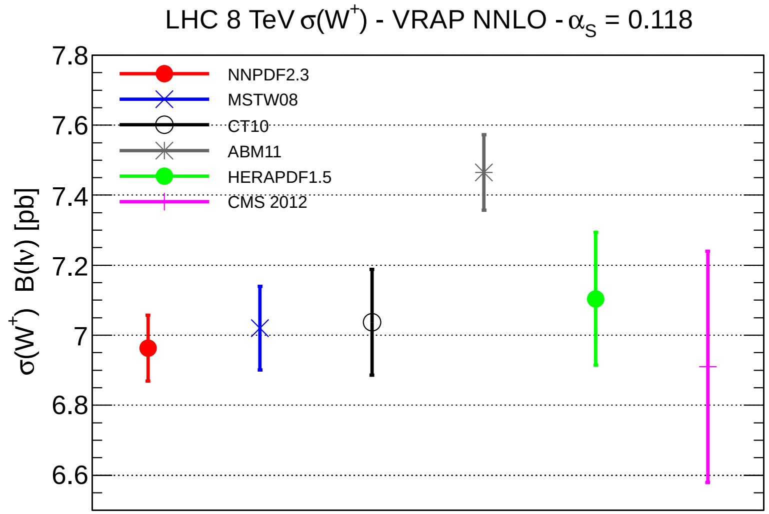
THEORY

- α_s VALUE: CTEQ: EXTERNAL PARAMETER, SEVERAL VALUES AVAILABLE; NNPDF: EXTERNAL PARAMETER, SEVERAL VALUES AVAILABLE, BEST-FIT DETERMINED; MSTW: FITTED, BUT ALSO VARIABLE AS EXT.PARAMETER; ABKM: FITTED, VARIABLE AS EXT.PARAMETER (ONLY CENTRAL VALUE); GJR: FITTED, NOT VARIABLE AS EXT. PARAMETER;
- HEAVY QUARKS: CTEQ: GM-VFN (SACOT-χ SCHEME); MSTW: GM-VFN (ACOT+TR' SCHEME); NNPDF: GM-VFN (FONLL SCHEME); ABKM: FFN ($N_f = 3, 4$ MATCHED WITH BMSN SCHEME); GJR: FFN ($N_f = 3$)
- NUCLEAR CORRECTIONS, HIGHER TWISTS, KINEMATIC CUTS, "INITIAL SCALE", ...

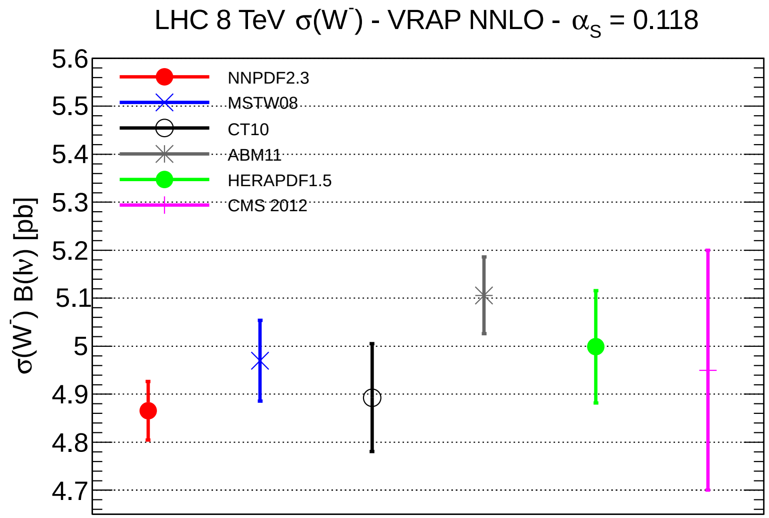
	MSTW08	CT10	NNPDF2.3	HERAPDF1.5	ABM11/12	JR09
NO. OF PDFS	7	6	7	5	6	5
STATISTICS	HESS.+DT	HESS.+DT	MC	HESS.+MODEL+PARM.	HESS.	HESS.+T
PDF PARMS.	20+8	25	259	14	24	12
HEAVY QUARKS	VFN TR	VFN ACOT	VFN FONLL	VFN TR	FFN	FFN

LHC EW STANDARD CANDLES

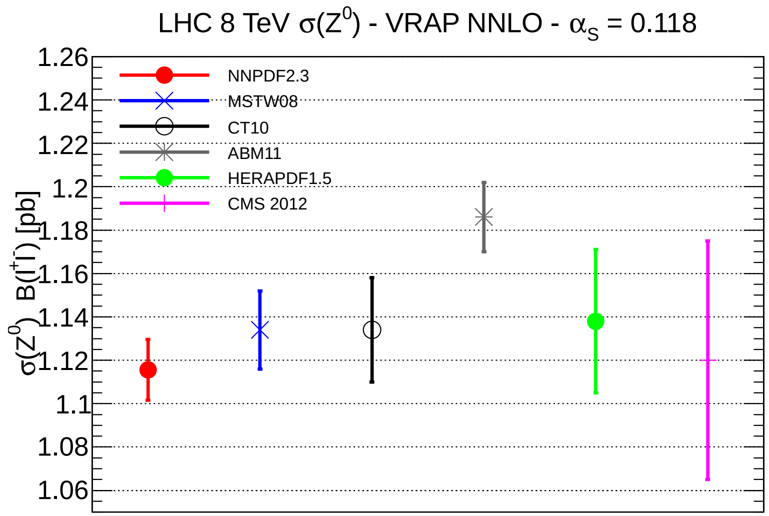
W^+



W^-



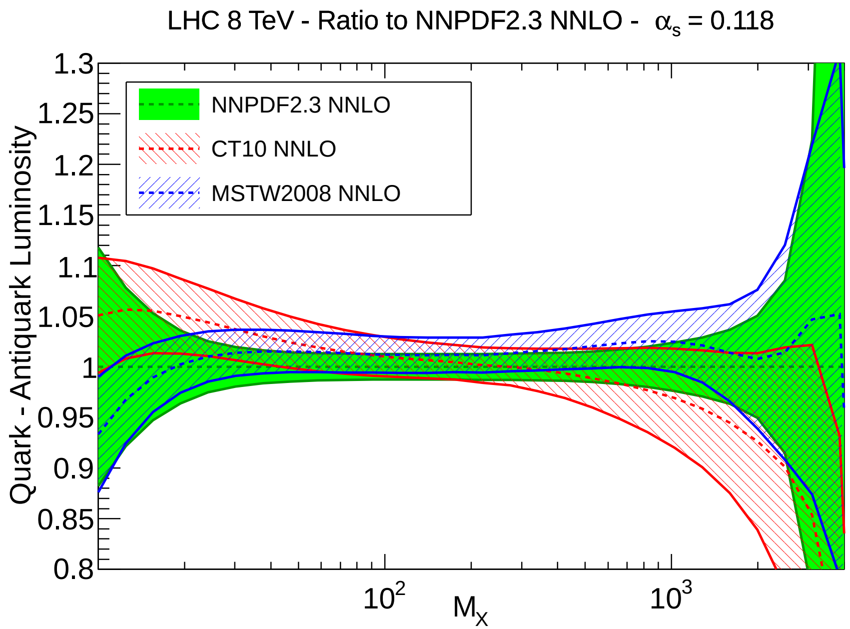
Z



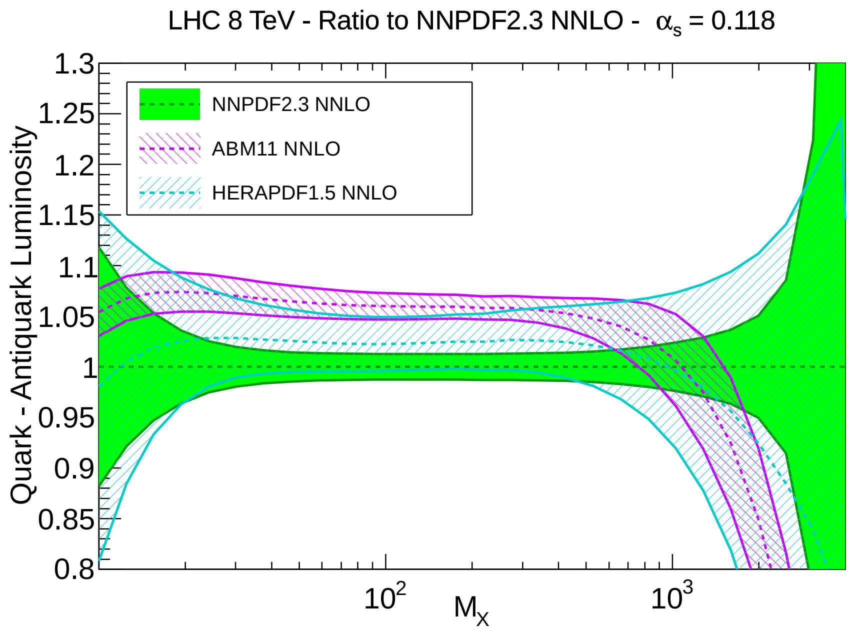
- AGREEMENT/DISAGREEMENT DRIVEN BY DATA
- DIS-ONLY FIT (HERAPDF) SAFE, BUT LARGE UNCERTAINTY
- FITS WITH SMALLER DATASETS PRONE TO TH. BIAS

PARTON LUMINOSITIES: QUARK SECTOR $(q\bar{q})$

GLOBAL PDF SETS
(ratio to NNPDF2.3)



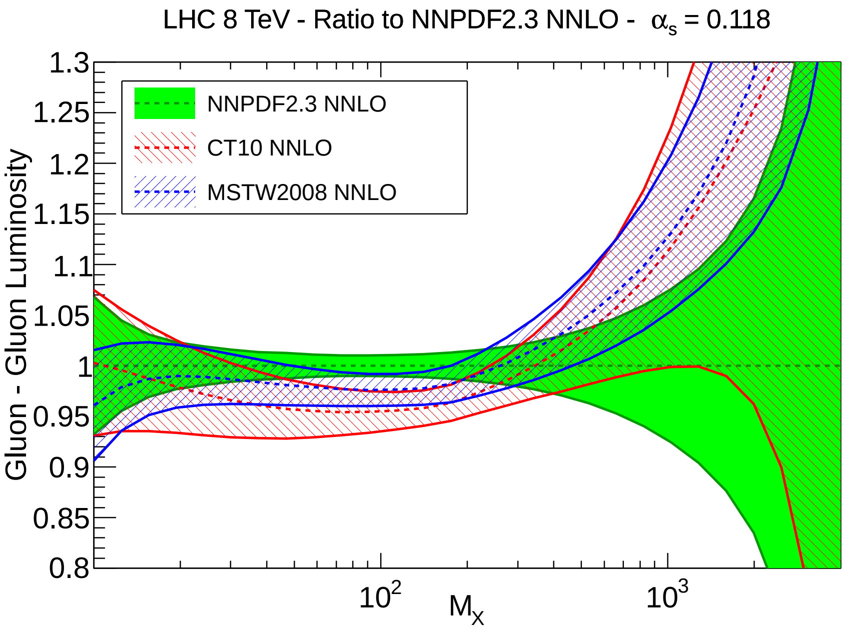
OTHER PDF SETS
(ratio to NNPDF2.3)



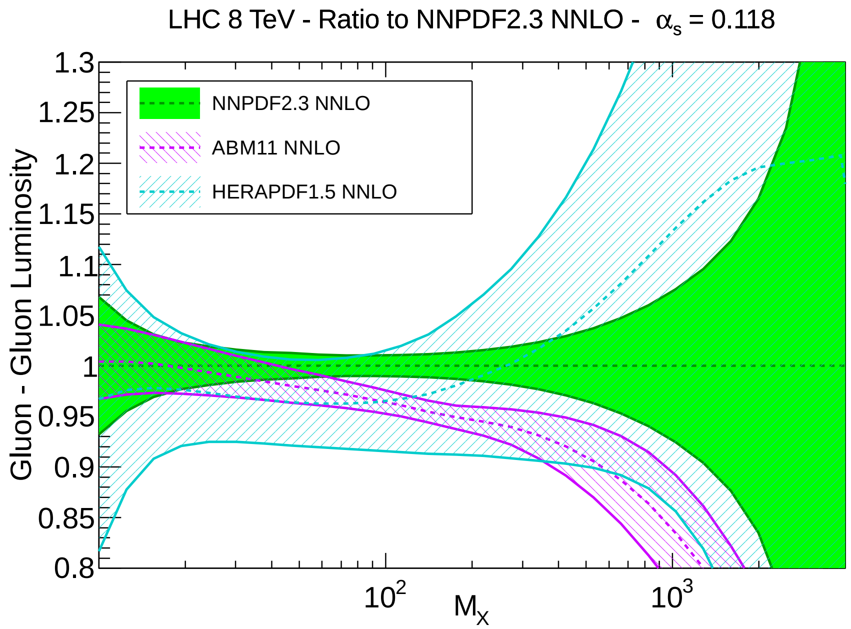
- CROSS-SECTIONS REFLECT UNDERLYING LUMINOSITIES
  FEWER DATA $\longrightarrow$ LARGER UNCERTAINTIES (OR SYSTEMATIC BIAS)
- GLOBAL SETS: GOOD AGREEMENT IN THE REGION OF THE EW SCALE
- UNCERTAINTIES BLOW UP FOR LARGE-MASS FINAL STATES

PARTON LUMINOSITIES: GLUON SECTOR

GLOBAL PDF SETS
(ratio to NNPDF2.3)



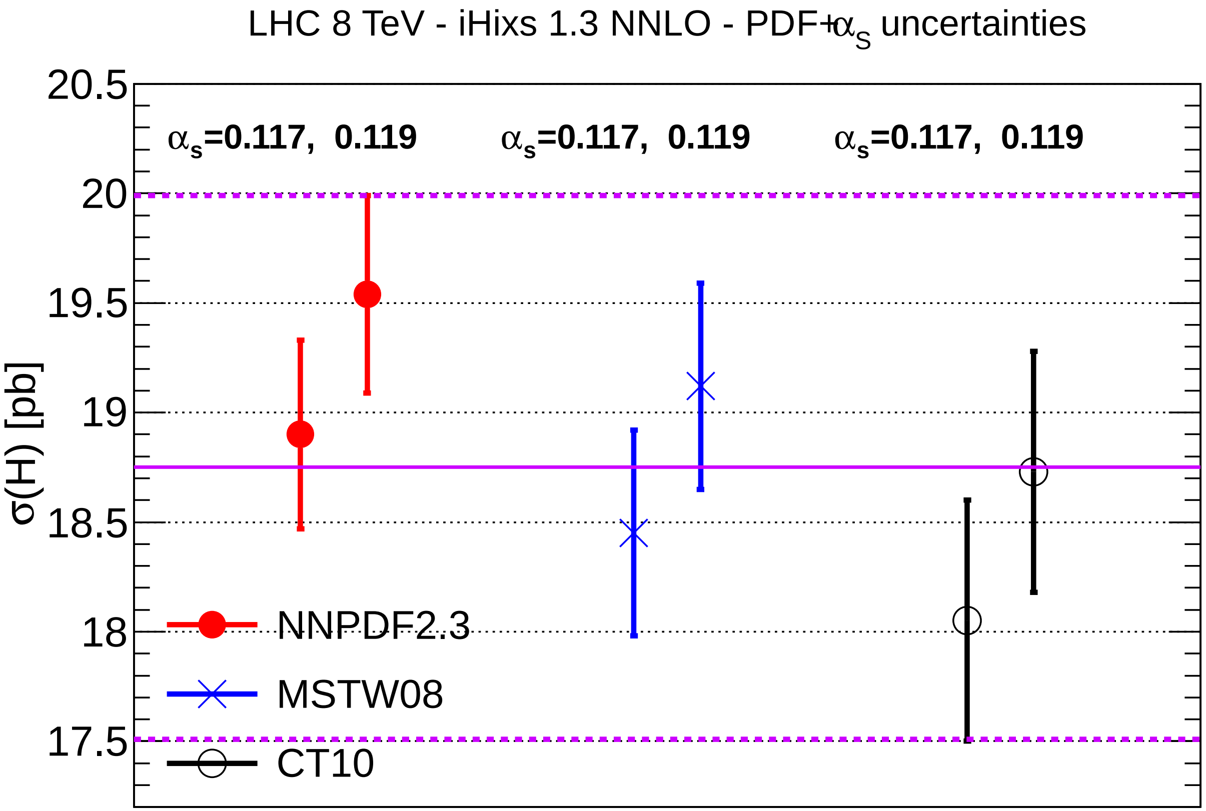
OTHER PDF SETS
(ratio to NNPDF2.3)



- FEWER DATA $\rightarrow$ LARGER UNCERTAINTIES (OR SYSTEMATIC BIAS)
- GLOBAL SETS: NOT SO GOOD AGREEMENT IN THE REGION OF THE EW SCALE
- UNCERTAINTIES BLOW UP FOR LARGE-MASS FINAL STATES

ISSUES

HIGGS IN GLUON FUSION

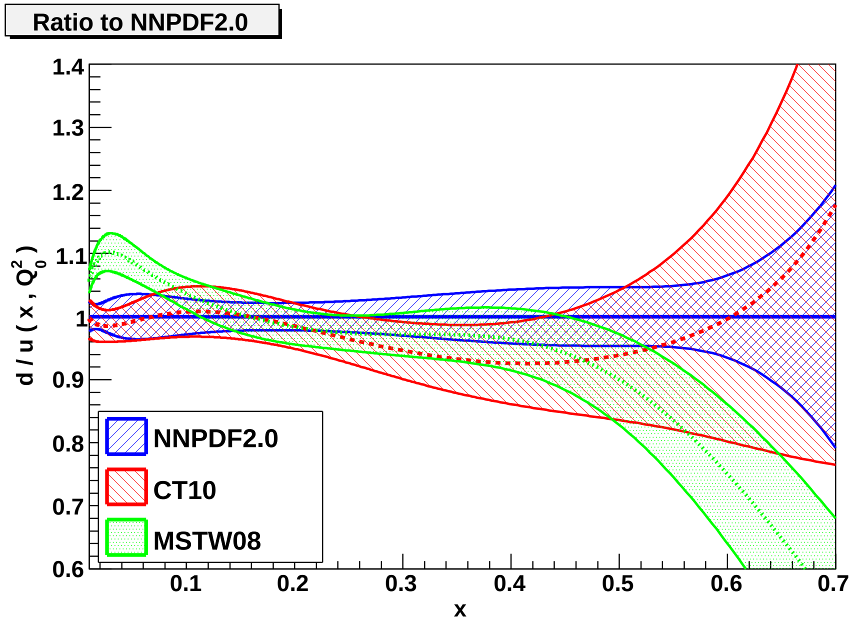


- DISCREPANCY NOT UNDERSTOOD DESPITE INTENSIVE BENCHMARKING
- CONSERVATIVE WAY OUT: TAKE THE ENVELOPE OF RESULTS (PDF4LHC PRESCRIPTION)

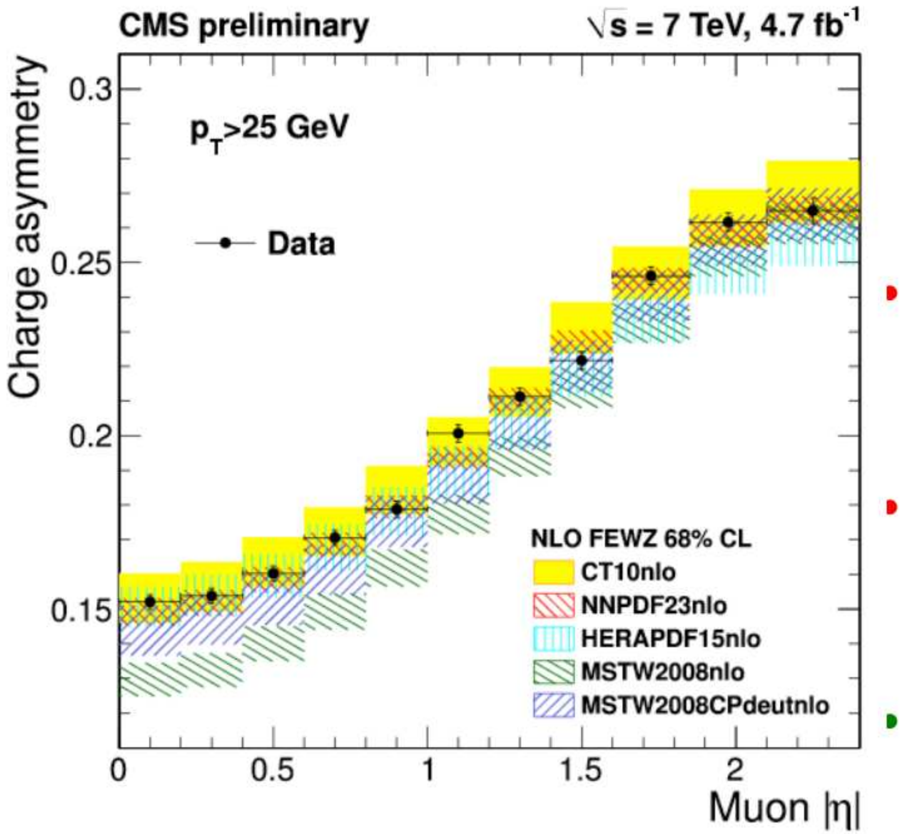
KNOWN ISSUES: METHODOLOGY

EXAMPLE: THE d/u RATIO

THE d/u RATIO



THE CMS W ASYMMETRY

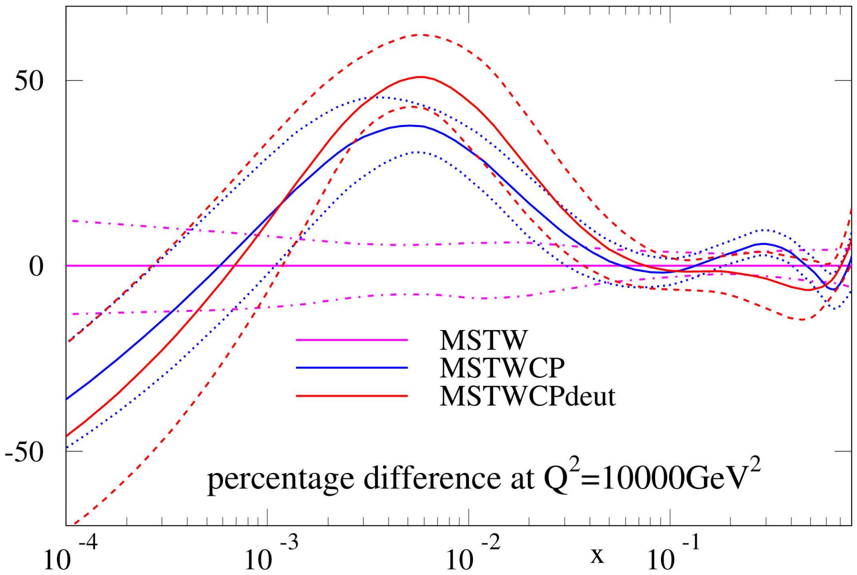


- LONG-STANDING DISCREPANCY IN THE d/u RATIO BETWEEN MSTW AND OTHER GLOBAL FITS
- RESOLVED BY W ASYMMETRY DATA
- EXPLAINED BY INSUFFICIENTLY FLEXIBLE PDF PARAMETRIZATION $\Rightarrow$ NEW MSTW08DEUT SET

KNOWN ISSUES: METHODOLOGY

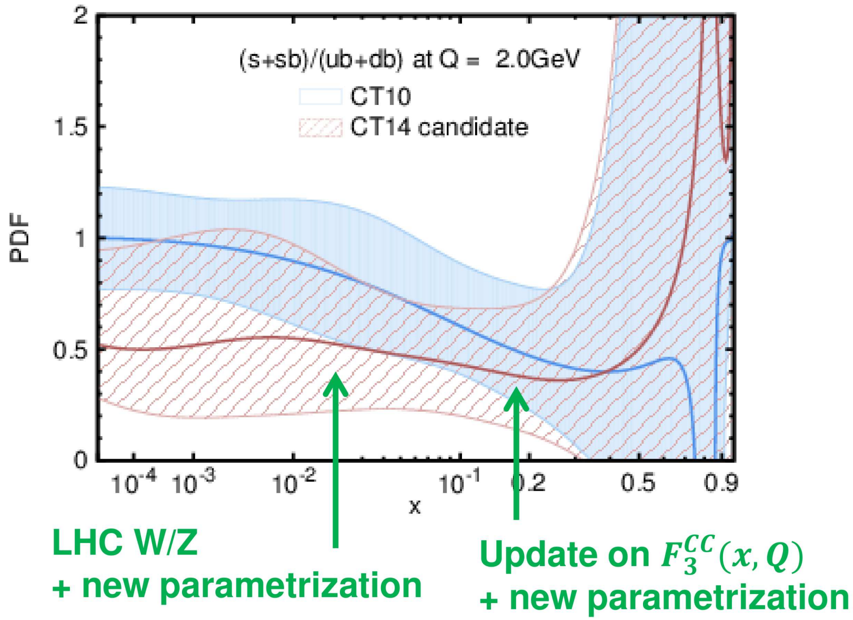
PARAMETRIZATION

MSTW08 DEUT VS DEFAULT



(MSTW, 2013)

CTx PDF SET

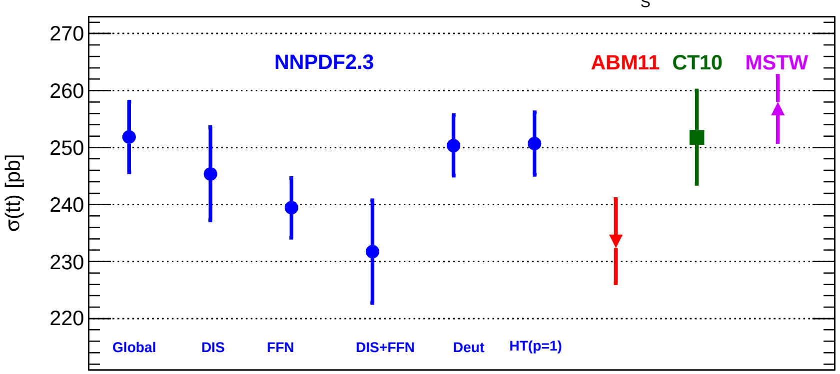


(P.Nadolsky, PDF4LHC, Nov.3, 2014)

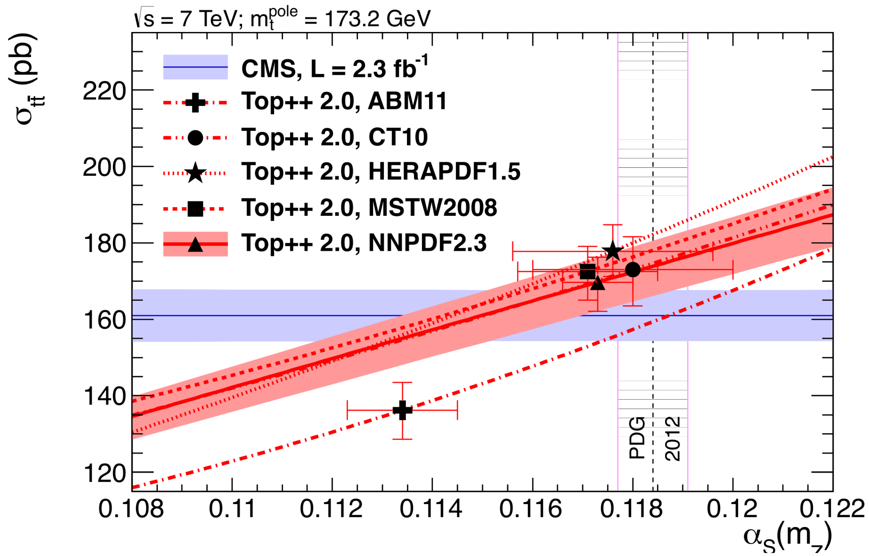
- IMPROVED PARAMETRIZATION (MORE PARAMETERS)
- $\Rightarrow$ MORE REALISTIC SHAPE
- MORE DATA $\Rightarrow$ BIGGER UNCERTAINTY

KNOWN ISSUES
THEORY AND DATA

FFN, DIS VS DEFAULT



TOP PRODUCTION



(CMS, 2014)

- FFN SCHEME NOT ADEQUATE FOR HIGH-ENERGY DATA
- DIS DATA ⇒ 'RUNAWAY' DIRECTION TOWARDS SMALL GLUON, SMALL α_s
- ⇒ CANNOT FIT TOP DATA

GETTING READY FOR RUN II: NNPDF3.0

THE NNPDF COLLABORATION: R. D. BALL, V. BERTONE, S. CARRAZZA, C. D. DEANS,

L. DEL DEBBIO, A. GUFFANTI, M. P. HARTLAND, Z. KASSABOV, P. GROTH-MERRILD,

J. I. LATORRE, J. ROJO AND M. UBIALI

SUMMARY

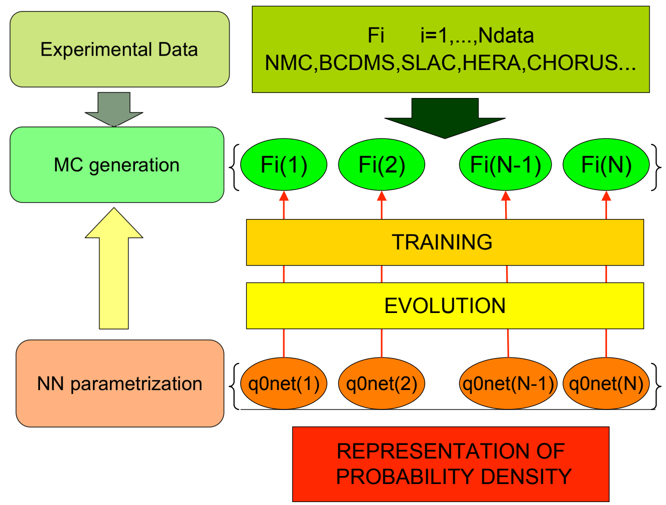
THE NNPDF METHODOLOGY ADDRESSES IN A QUANTITATIVE & SYSTEMATIC WAY ISSUES OF

- METHODOLOGY: CLOSURE TESTS
- THEORY CONSISTENCY: BENCHMARKS
  CASE STUDY I: JETS AND NNLO
- DATA: COMPATIBILITY & IMPACT ANALYSIS TOOLS
  CASE STUDY II: THE STRANGE PDF
  CASE STUDY III: CONSERVATIVE PARTONS
  CASE STUDY IV: ASSESSING DATA IMPACT

THE NNPDF METHODOLOGY
A BRIEF SUMMARY

MONTE CARLO APPROACH

- PSEUDODATA REPLICAS ARE GENERATED USING FULL INFO ON CORRELATED SYSTEMATICS
  $\Rightarrow$ MONTECARLO REPRESENTATION OF COVARIANCE MATRIX
- A PDF REPLICA SET IS FITTED TO EACH PSEUDO-DATA REPLICA
- THE SET OF PDF REPLICAS CAN BE USED TO COMPUTE ANY SET OF OBSERVABLES
  CENTRA VALUES (MEANS), UNCERTAINTIES (VARIANCES), CORRELATIONS (COVARIANCES), CONFIDENCE LEVELS. . .



NEURAL NETWORK PARAMETRIZATION

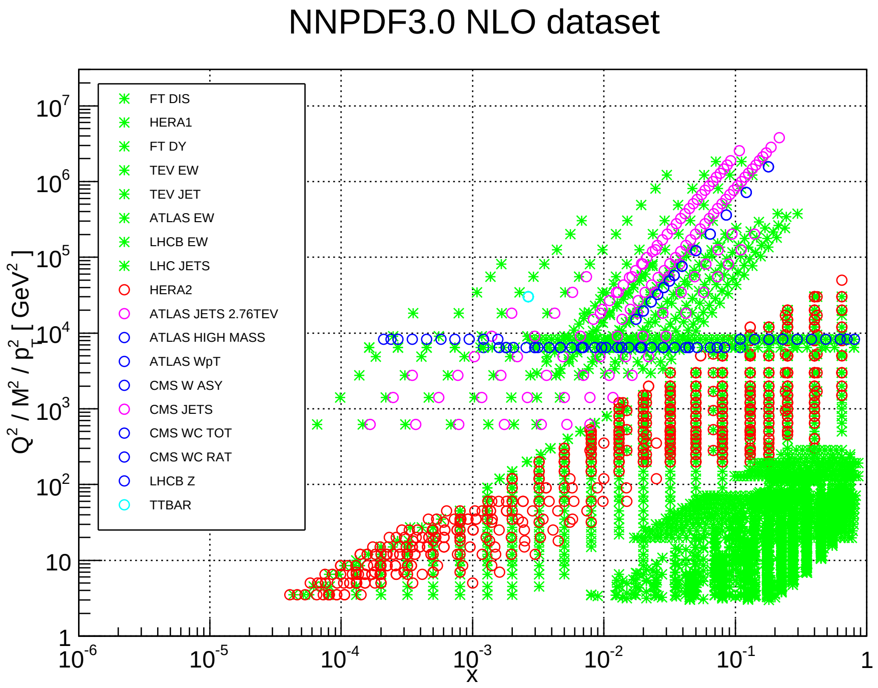
- EACH PDF IS PARAMETRIZED BY A NEURAL NETWORK
  37 PARAMETERS WITH DEFAULT $2-5-3-1$ ARCHITECTURE
- MINIMIZATION IS PERFORMED USING GENETIC ALGORITHMS
- BEST-FIT IS NOT MINIMUM OF χ^2 (WOULD BE FITTING NOISE) $\Rightarrow$ CROSS-VALIDATION
  DIVIDE DATA IN TWO SETS, FIT TRAINING SET, MONITOR VALIDATION SET, STOP WHEN VALIDATION χ^2 STARTS RISING

THE NNPDF3.0 DATASET

A BRIEF SUMMARY

NEW IN NNPDF3.0

- COMBINED HERA CHARM PRODUCTION (55 D.P)
- HERA II ZEUS+H1 STRUCTURE FUNCTIONS (778 D.P.)
- ATLAS 2.76TEV JETS (59 D.P.)
- ATLAS HIGH-MASS DRELL-YAN (5 D.P.)
- ATLAS W p_T (9 D.P.)
- CMS W MUON ASYMMETRY (11 D.P.)
- CMS DOUBLE-DIFFERENTIAL DRELL-YAN (110 D.P.)
- CMS JETS (133 D.P.)
- CMS $W + c$ (10 D.P.)
- LHCB Z RAPIDITY (9 D.P.)
- ATLAS & CMS TOP TOTAL XSECT (3+3 D.P.)
- TOTAL DATASET:
  4276/4078 (NLO/NNLO)



NNPDF3.0 THEORY AND METHODOLOGY

A BRIEF SUMMARY

NEW IN NNPDF3.0

- UNCERTAINTIES: ALL CAN BE ADDITIVE OR MULTIPLICATIVE
- EW CORRECTIONS INCLUDED
- FULL MIGRATION OF CODE TO C++
- PDF PARAMETRIZATION SCALE ($Q^2 = 1$ GeV) & BASIS (EVOLUTION EIGENSTATES)
- PREPROCESSING: BASIS INDEPENDENT, SELF-CONSISTENTLY DETERMINED
- GENETIC ALGORITHM: NODAL MUTATION
- IMPLEMENTATION OF CROSS-VALIDATION: LOOKBACK STOPPING

METHODOLOGY: CLOSURE TESTING

CLOSURE TESTS:

THE BASIC IDEA

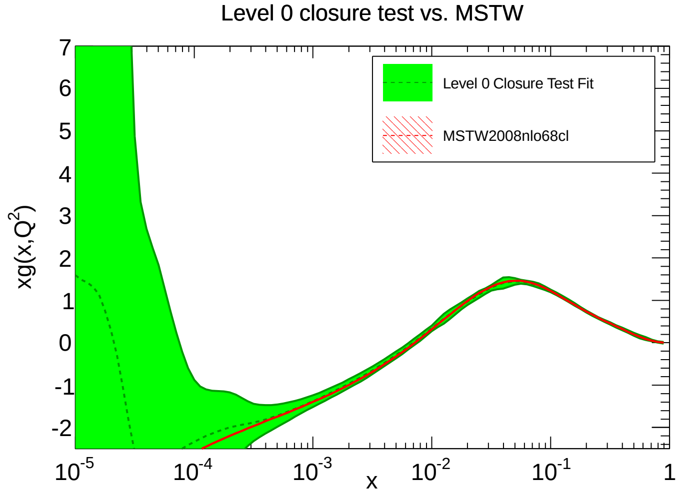
- ASSUME PDFS KNOWN: GENERATE FAKE EXPERIMENTAL DATA
- CAN DECIDE DATA UNCERTAINTY (ZERO, OR AS IN REAL DATA, OR . . .)
- FIT PDFS TO FAKE DATA
- CHECK WHETHER FIT REPRODUCES UNDERLYING "TRUTH":
  - CHECK WHETHER TRUE VALUE GAUSSIANLY DISTRIBUTED ABOUT FIT
  - CHECK WHETHER UNCERTAINTIES FAITHFUL
  - CHECK STABILITY

    (INDEP. OF METHODOLOGICAL DETAILS)

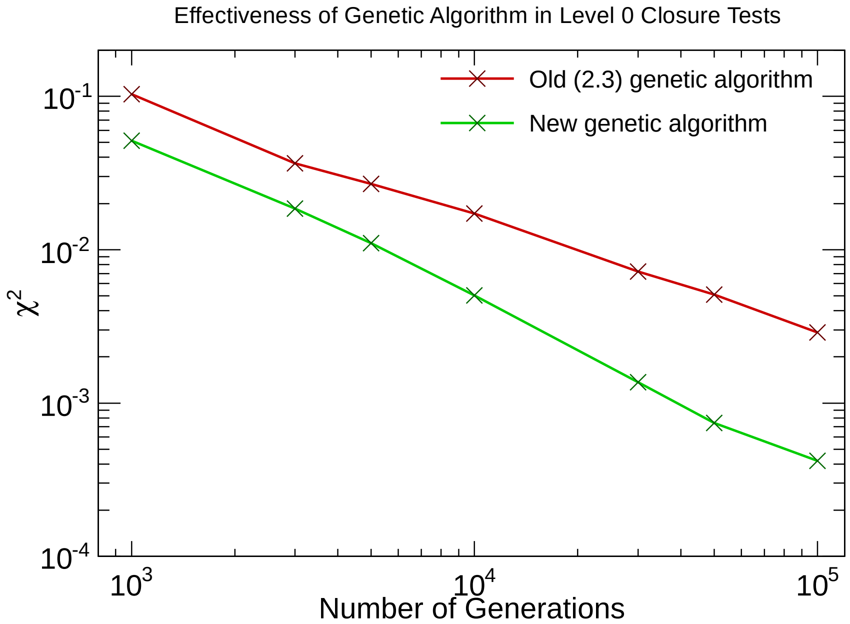
LEVEL-0 CLOSURE TESTS

- ASSUME VANISHING EXPERIMENTAL UNCERTAINTY
- MUST BE ABLE TO GET $\chi^2 = 0$
- UNCERTAINTY AT DATA POINTS TENDS TO ZERO (NOT NECESSARILY ON PDF!)
  DEFINE $\phi \equiv \sqrt{\langle\chi^2_{rep}\rangle - \chi^2}$, EQUALS FIT UNCERTAINTY/DATA UNCERTAINTY; CHECK $\phi \to 0$
- BEST FIT ON TOP OF "TRUTH" IN DATA REGION

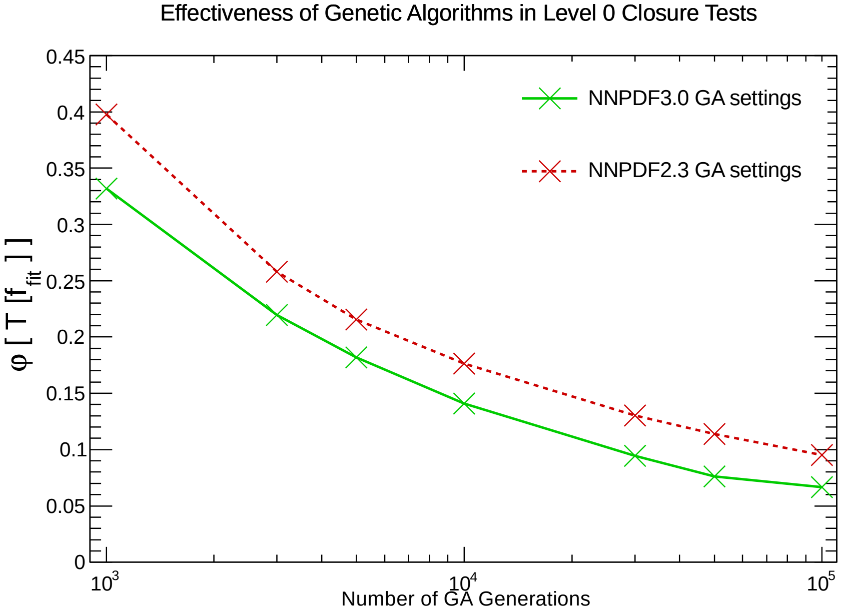
THE GLUON



χ^2 VS TRAINING LENGTH



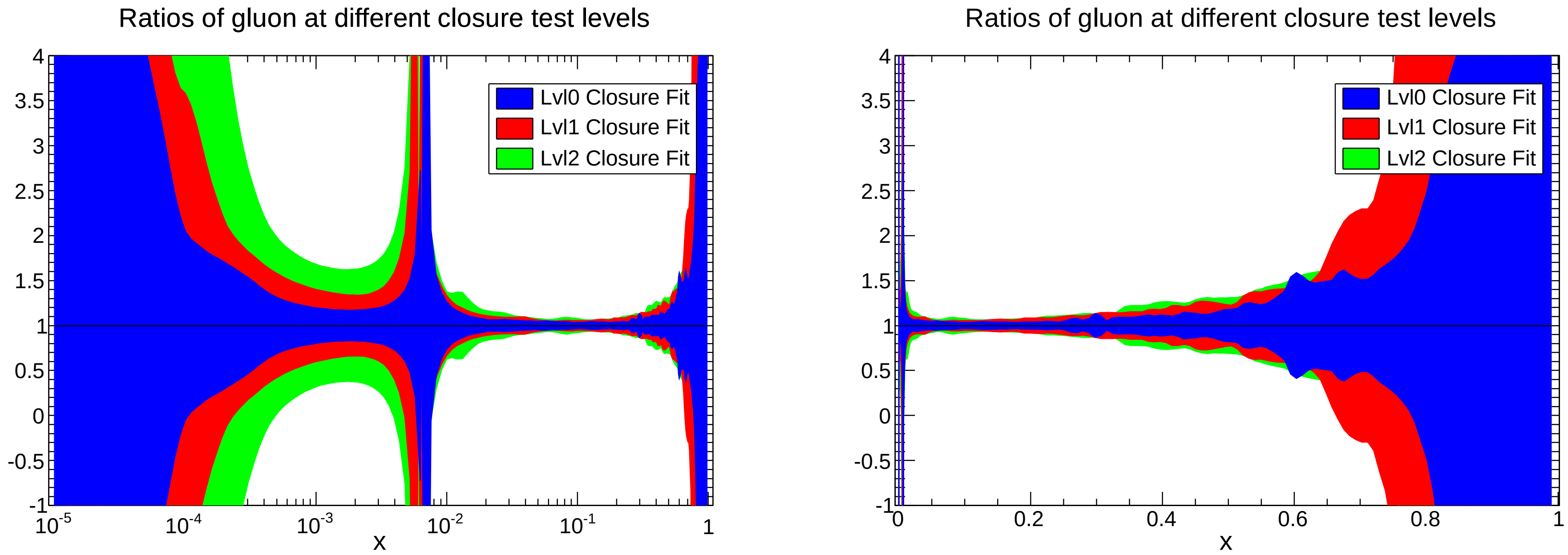
FRACTIONAL UNCERTAINTY VS TRAINING LENGTH



LEVEL-0, LEVEL-1 AND LEVEL-2

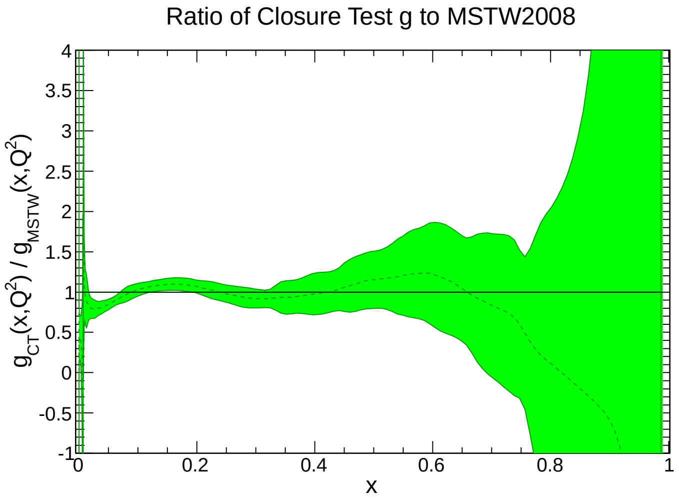
- LEVEL 0: FAKE DATA GENERATED WITH NO UNCERTAINTY
  $\rightarrow$ INTERPOLATION AND EXTRAPOLATION UNCERTAINTY
- LEVEL 1-2: FAKE DATA GENERATED WITH SAME UNCERTAINTY AS REAL DATA (INCLUDING CORRELATIONS)
- LEVEL 1: NO PSEUDODATA REPLICAS:
  $\Rightarrow$ REPLICAS FITTED TO SAME DATA OVER AND OVER AGAIN
  $\rightarrow$ FUNCTIONAL UNCERTAINTY DUE TO INFINITY OF EQUIVALENT MINIMA
- LEVEL 2: STANDARD NNPDF METHODOLOGY
  $\Rightarrow$ REPLICAS FITTED TO PSEUDODATA REPLICAS
  $\rightarrow$ DATA UNCERTAINTY
- THREE SOURCES OF UNCERTAINTY COMPARABLE IN DATA REGION

THE GLUON: LEVEL 0, LEVEL 1 AND LEVEL 2



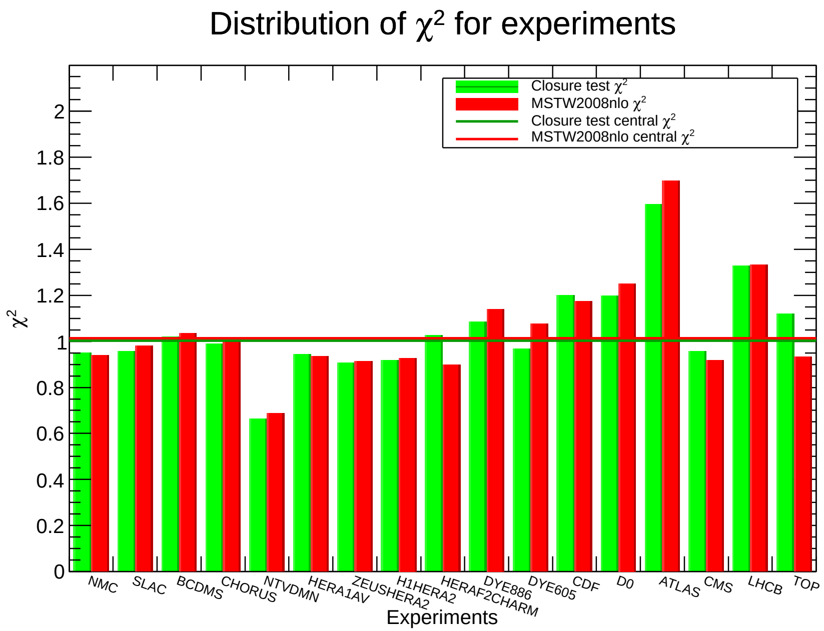
LEVEL-2: CENTRAL VALUES AND UNCERTAINTIES

THE GLUON: FITTED/"TRUE"

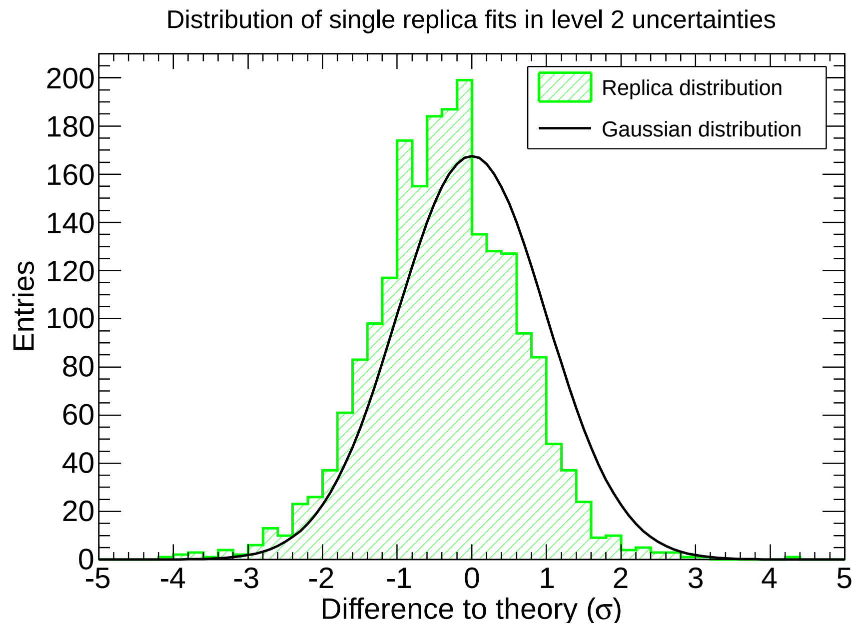


- CENTRAL VALUES:
  COMPARE FITTED VS. "TRUE" χ^2
  BOTH FOR INDIVIDUAL EXPERIMENTS
  & TOTAL DATASET
  FOR TOTAL $\Delta\chi^2 = 0.001 \pm 0.003$
- UNCERTAINTIES: DISTRIBUTION OF DEVIATIONS BETWEEN FITTED AND "TRUE" PDFs
  SAMPLED AT 20 POINTS BETWEEN 10^{-5} AND 1
  FIND 0.699% FOR ONE-SIGMA,
  0.948%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

LEVEL-2 FITTED χ^2 VS "TRUE"



NORM. DISTRIBUTION OF DEVIATIONS



LEVEL-2 STABILITY TESTS

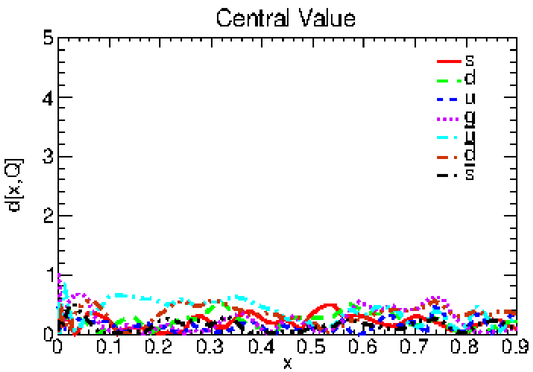
- CHANGE UNDERLYING PDF SET (CT10, NNPDF2.3)
- INCREASE MAXIMUM GA TRAINING LENGTH TO 80K
  TESTS EFFICIENCY OF CROSS-VALIDATION
- INCREASE NN ARCHITECTURE TO 2-20-15-1
  NUMBER OF FREE PARAMETRES INCREASE BY MORE THAT $10\times$
- CHANGE PDF PARAMETRIZATION BASIS
  OLD: ISOTRIPLET, $\bar{u}-\bar{d}$,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

STATISTICAL EQUIVALENCE!

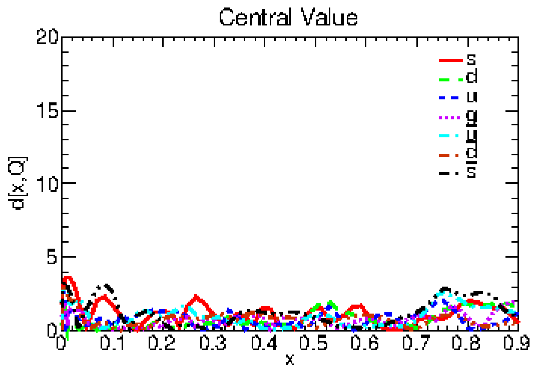
DISTANCES BETWEEN REF. AND NEW FIT:

difference in unites of standard deviation of the mean

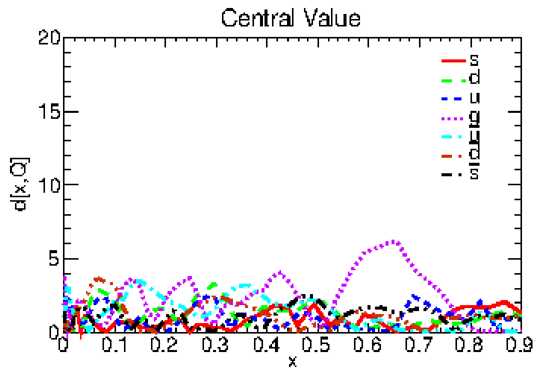
30K GENS VS 80K GENS



2.3 BASIS VS 3.0 BASIS



300 VS 37 PARMS

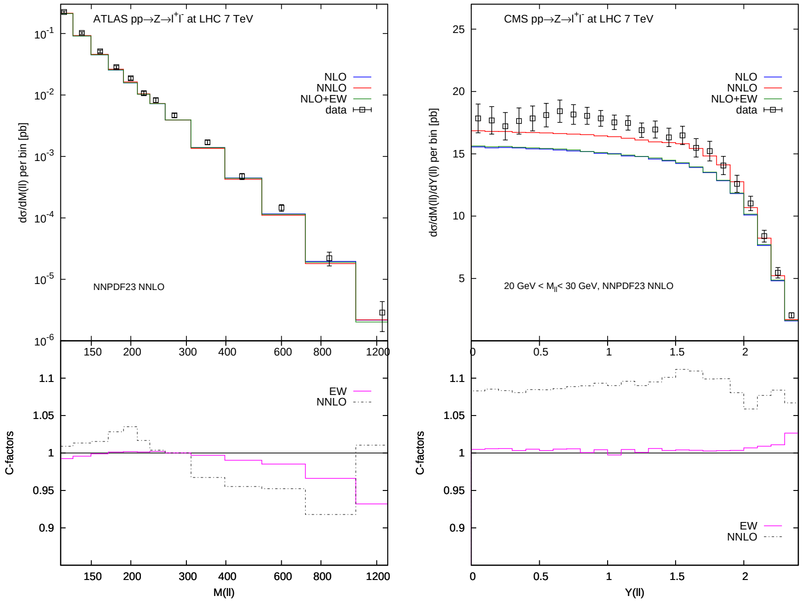


THEORY BENCHMARKING

CORRECTIONS AND CUTS

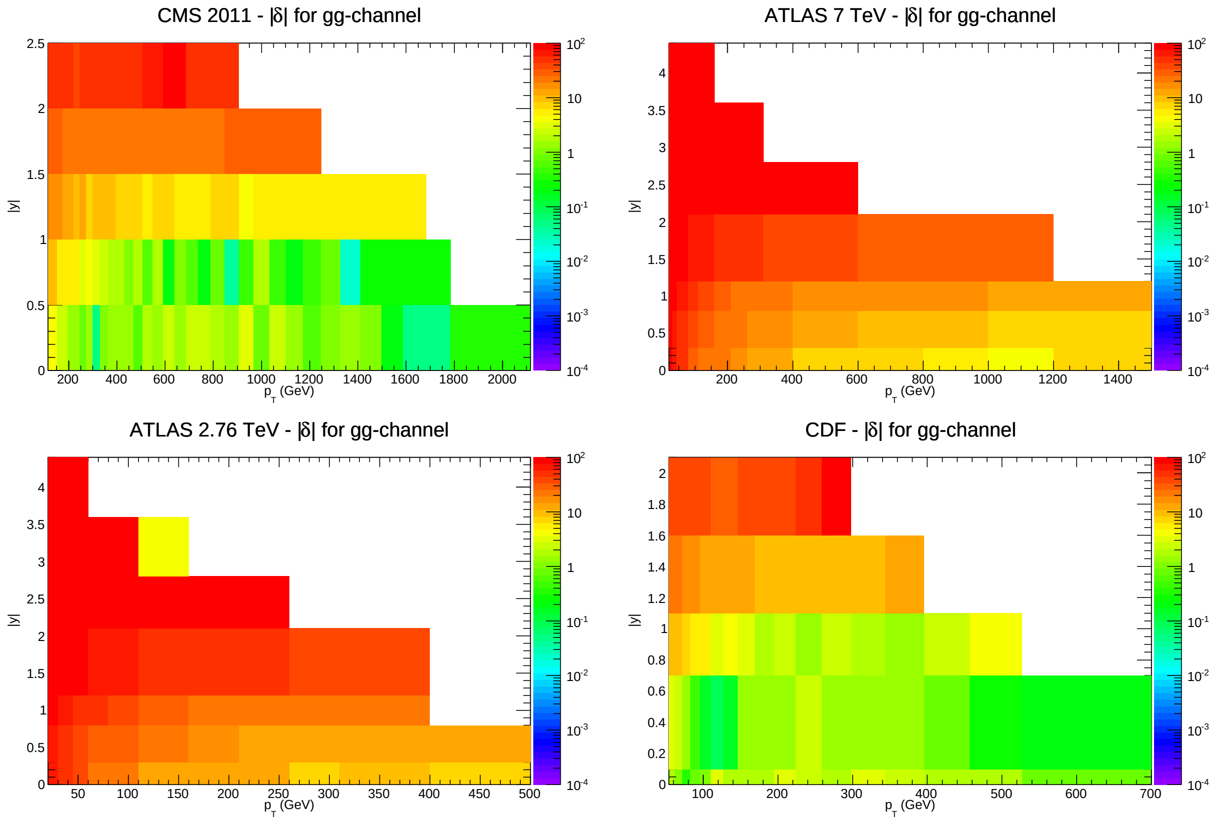
- PDFs provided at LO, NLO, NNLO in α_s
- NNLO QCD corrns benchmarked between codes:
  for DY MCFM vs FEWZ at NLO; FEWZ & DYNNLO for NNLO;
- size of NNLO monitored: in NLO fit, discard if $\gg$ than expt uncertainties
  lowest Q^2 bin of CMS 2dDY discarded
- virtual pure EW corrections included; FSR-corrected data used;
  QED corrections monitored
  highest Q^2 bin of CMS 2dDY discarded

NLO, NNLO & EW corrns
ATLAS and CMS
high mass DY

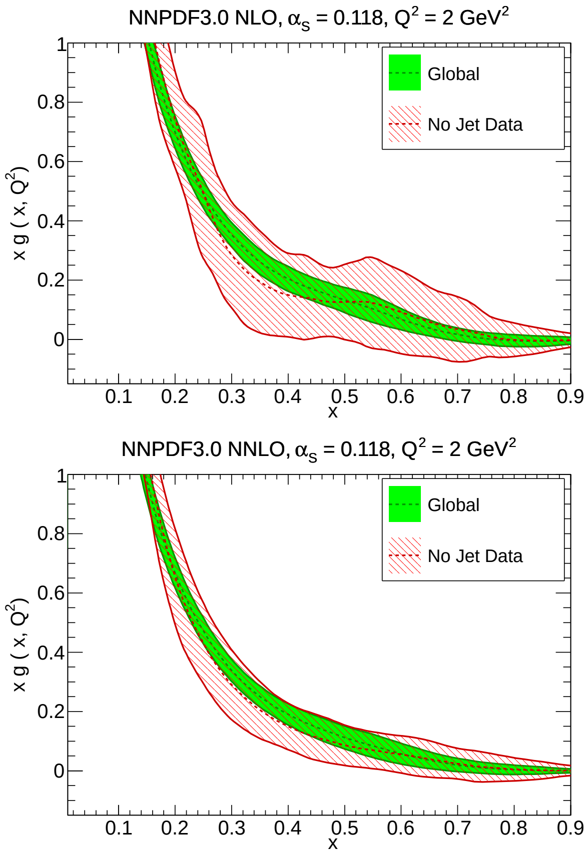


JET DATA AT NLO AND NNLO

PERCENTAGE ACCURACY OF THRESHOLD APP. IN GLUON CHANNEL



IMPACT OF THE JET DATA: NLO&NNLO



- EXACT NNLO CORRECTIONS NOW KNOWN IN GLUON CHANNEL (GEHRMANN, GLOVER, DE RIDDER, PIRES, 2014)
- THRESHOLD APPROX AVAILABLE IN ALL CHANNELS (DE FLORIAN ET AL, 2014)
- ONLY ACCURATE AT HIGH p_T, CENTRAL RAPIDITY, LARGER JET RADIUS (CARRAZZA & PIRES, 2014)
- AT NNLO RETAIN ONLY BINS SUCH THAT ACCURACY BETTER THAN 10% CORRECTION THERE SMALLER THAN 15% $\Rightarrow$ ATLAS ($R = 0.4$) MOSTLY CUT OUT
- IMPACT OF JET DATA STILL SIZABLE

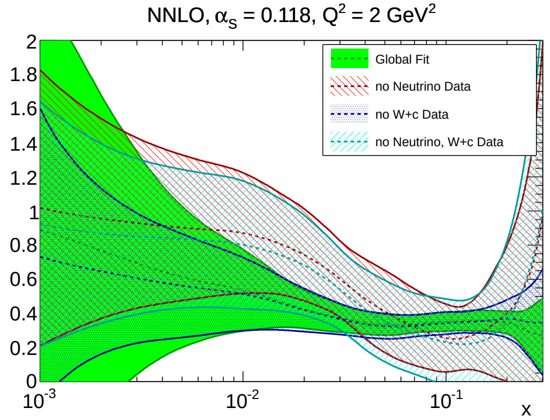
DATA CONSISTENCY & IMPACT ANALYSIS

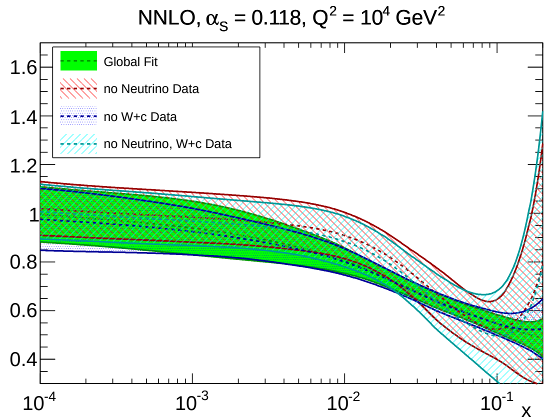
NUCLEON STRANGENESS

	$\chi^2_{\rm exp}$			
	GLOBAL	NO NEUTRINO	NO W+c	NO NEUTRINO/W+c
CHORUS	1.13	3.87	1.09	3.45
NUTEV	0.62	4.31	0.66	6.45
ATLAS W, Z 2010	1.21	1.05	1.24	1.08
CMS W+c 2011	0.86	0.50	0.90	0.61

STRANGENESS RATIO

AT LOW & HIGH SCALE





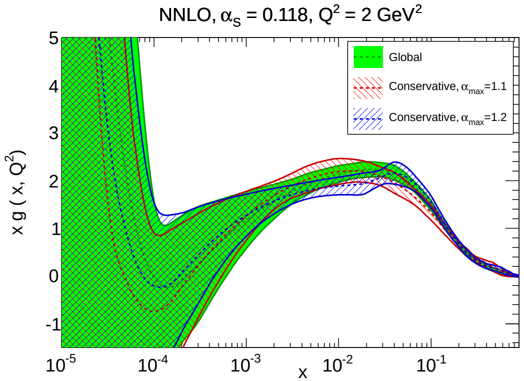
- IN GLOBAL FITS, STRANGENESS DETERMINED IN EQUAL PROPORTION BY NEUTRINO & W/Z PRODUCTION DATA
- NOW SPECIFIC INFORMATION FROM $W + c$
  BUT ONLY 10 CMS DATAPOINTS;
  ATLAS NOT YET INCLUDED BECAUSE DATA ARE HADRON-LEVEL
- DEFINE STRANGENESS RATIO $r(x, Q^2) = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$
- ALL DETERMINATIONS CONSISTENT WITHIN UNCERTAINTIES
- AT PRESENT NEUTRINO DATA CONTROL BOTH CENTRAL VALUE & UNCERTAINTY
- W/Z PRODUCTION DATA FAVOR LARGER r BUT WITH MUCH LARGER UNCERTAINTY
- CMS $W + c$ DATA HAVE VERY LITTLE IMPACT, ON GLOBAL FIT OR ON FIT W/O NEUTRINO DATA (PERHAPS FAVOR HIGHER r)

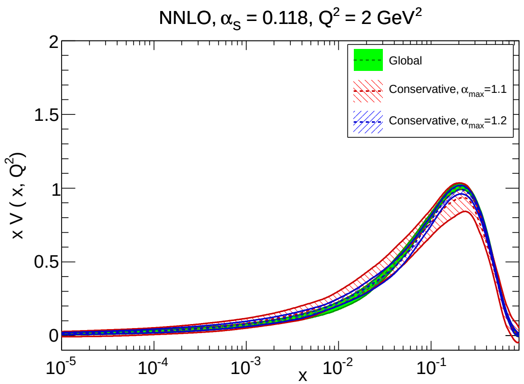
CONSERVATIVE PARTONS

- RESCALE ALL UNCERTAINTIES $\sigma \to \alpha\sigma$: $\chi^2 \to \chi^2/\alpha^2$ FOR A GIVEN EXPERIMENT
- DETERMINE PROBABILITY DISTRIBUTION $P(\alpha)$ (USING BAYES)
- DISCARD ALL EXPERIMENT FOR WHICH $P(\alpha)$ PEAKS WELL ABOVE ONE
  TWO OUT OF MEDIAN, MODE, MEAN, GREATER THAN $\alpha_{threshold}$
- $\chi^2 = 1.29$ FOR NNLO GOBAL, BECOMES $\chi^2 = 1.16$ FOR $\alpha_{threshold} = 1.3$, $\chi^2 = 1.10$ FOR $\alpha_{threshold} = 1.2$, $\chi^2 = 1.01$ FOR $\alpha_{threshold} = 1.1$, BUT CONSIDERABLE DETERIORATION OF UNCERTAINTIES

CONSERV. VS. DEFAULT

GLUON AND VALENCE





α PEAK FOR EXPERIMENTS DISCARDED IN CONS. FIT

WHEN INCLUDED OR EXCLUDED FROM FIT

	NNLO global fit			NNLO cons. fit $\alpha_{max} = 1.1$		
Experiment	mean	mode	median	mean	mode	median
NMC $\sigma^{NC,p}$	1.27	1.26	1.27	1.50	1.45	1.48
SLAC	1.13	1.09	1.12	1.61	1.37	1.48
BCDMS	1.20	1.19	1.20	2.02	1.86	1.92
CHORUS	1.10	1.09	1.09	2.55	1.69	2.32
ZEUS HERA-II	1.25	1.24	1.25	1.38	1.33	1.36
H1 HERA-II	1.35	1.34	1.34	1.51	1.47	1.49
HERA σ^c_{NC}	1.14	1.11	1.13	1.13	1.09	1.12
E886 p	1.15	1.14	1.15	2.18	1.62	2.03
CDF Z rapidity	1.39	1.32	1.36	1.56	1.40	1.50
CDF Run-II k_t jets	1.15	1.12	1.14	1.25	1.18	1.22
ATLAS W, Z 2010	1.17	1.12	1.15	1.38	1.25	1.32
ATLAS high-mass DY	1.00	1.34	1.63	1.63	1.19	1.45
CMS W muon asy	1.60	1.40	1.53	2.90	2.48	2.81
CMS W+c total	1.50	1.09	1.33	1.85	1.37	1.67
CMS W+c ratio	2.00	1.39	1.69	2.12	1.58	1.94
CMS 2D DY 2011	1.28	1.27	1.28	1.29	1.28	1.29
LHCb	1.20	1.12	1.17	1.58	1.22	1.48

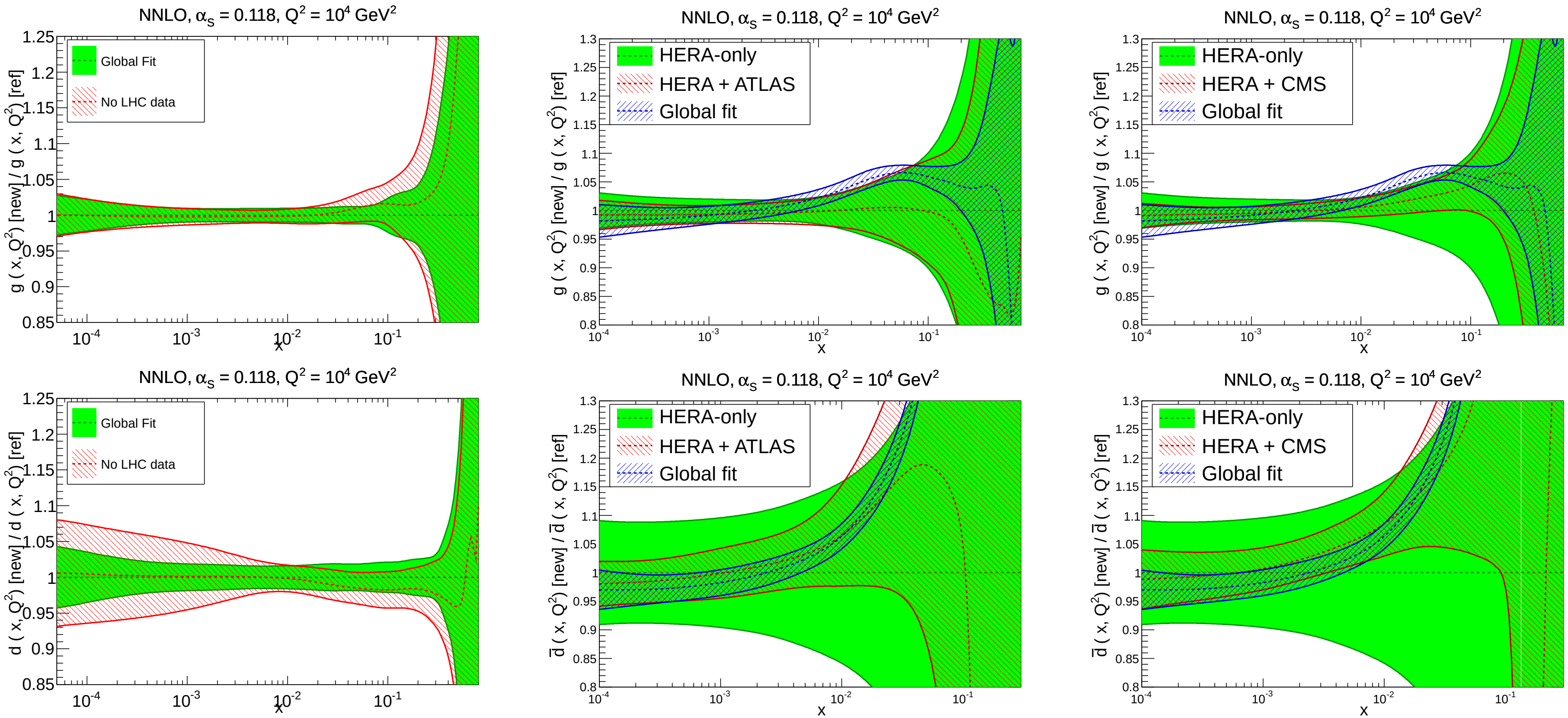
THE IMPACT OF LHC (AND HERA) DATA

- OVERALL MEASURE OF IMPACT:
  $\phi \Rightarrow$ FIT UNCERTAINTY/DATA UNCERTAINTY
- HERA-II IMPACT SIZABLE
- IMPACT OF LHC DATA MODERATE BUT VISIBLE
- IMPACT OF CMS OR ATLAS COMPARABLE TO (MODERATE) IMPACT OF NON-LHC, NON-HERA DATA

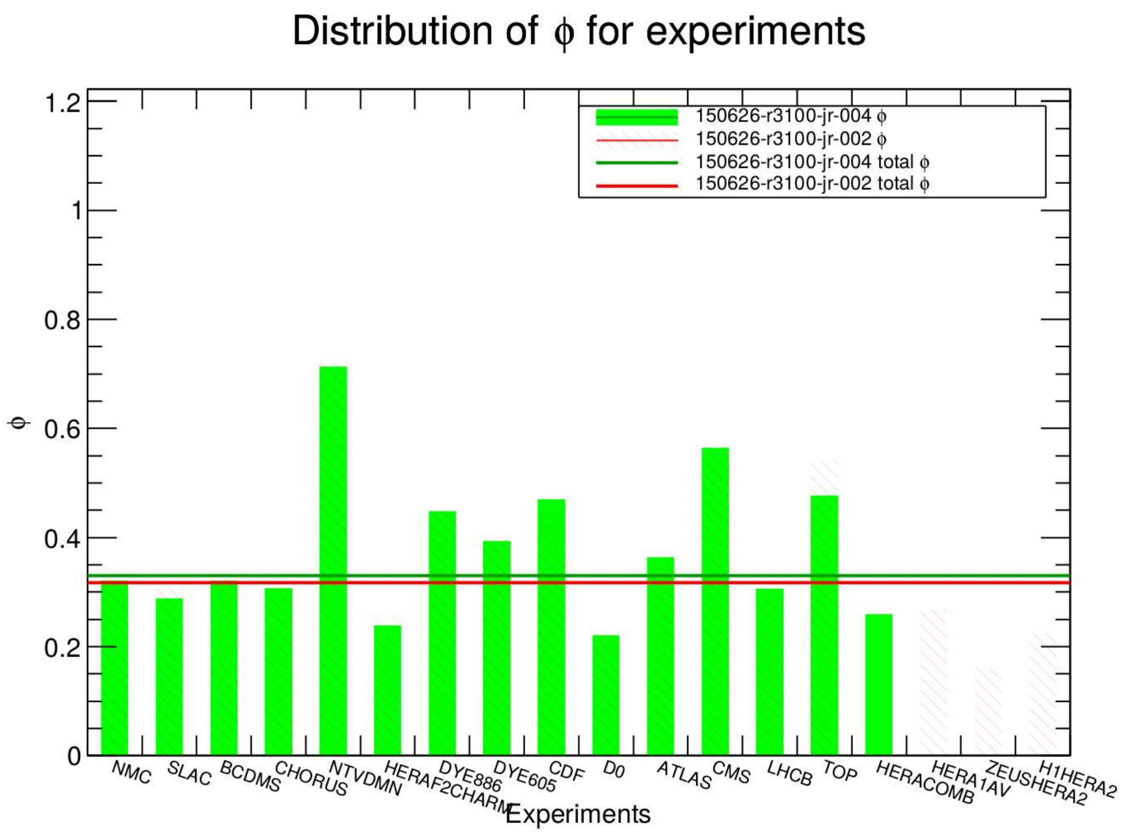
FRACTIONAL UNCERTAINTY

Dataset	φ_{χ^2} NLO	φ_{χ^2} NNLO
Global	0.291	0.302
HERA-I	0.453	0.439
HERA all	0.375	0.343
HERA+ATLAS	0.391	0.318
HERA+CMS	0.315	0.345
Conservative	0.422	0.478
no LHC	0.312	0.316

GLOBAL VS NO LHC: g& d GLOBAL VS HERA+ATLAS: g& $\bar{d}$ GLOBAL VS HERA+CMS: g& $\bar{d}$



IMPACT OF THE COMBINED HERA DATA

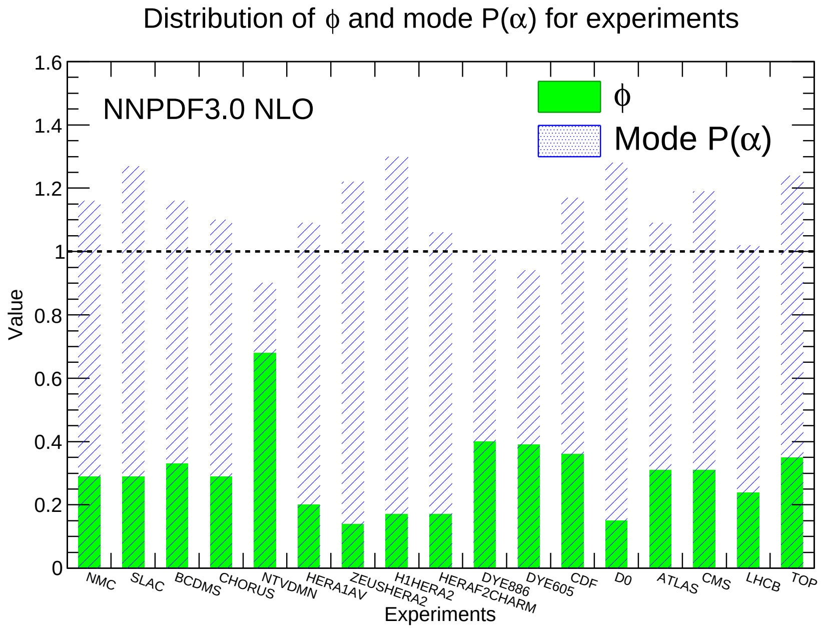


- REPLACE ALL HERA DATA WITH NEW COMBINED SET
- ϕ OF HERA2 NON-COMBINEDCDATA QUITE SMALL $\Rightarrow$ SMALL IMPACT
- ϕ OF COMBINED HERA1 & TOTAL COMBINED HERA QUITE SIMILAR $\Rightarrow$ IMPACT OF COMBINATION SMALL

• DATA: WHERE LIES THE PROMISE

- CAN USE α & ϕ INDICATORS TO ASSESS OBJECTIVELY WHICH DATA COULD HAVE BIGGER IMPACT
- LARGE α MODE $\Rightarrow$ MUST IMPROVE COMPATIBILITY
- SMALL ϕ $\Rightarrow$ MUST REDUCE UNCERTAINTY

$P(\alpha)$ MODE & ϕ



	NNLO global fit		
Experiment	N_{dat}	$P(\alpha)$ mode	ϕ
ATLAS W, Z 2010	30	1.12	0.32
ATLAS 7 TeV jets 2010	90	0.92	0.25
ATLAS 2.76 TeV jets	59	0.57	0.34
ATLAS high-mass DY	5	1.34	0.11
CMS W electron asy	11	0.87	0.29
CMS W muon asy	11	1.40	0.51
CMS jets 2011	133	1.07	0.37
CMS $W+c$ total	5	1.09	0.24
CMS $W+c$ ratio	5	1.39	0.39
CMS 2D DY 2011	88	1.27	0.13
LHCb W, Z rapidity	19	1.12	0.24
$\sigma(t\bar{t})$	6	0.75	0.35

SOME PRELIMINARY INDICATIONS...

- 2.76TEV JET DATA SEEEM TO HAVE OVERESTIMATED UNCERTAINTIES, POTENTIALLY HIGH IMPACT
- TOP DATA: SUPRISINGLY HIGH IMPACT GIVEN SMALL DATA SAMPLE
- HIGH-MASS DY $\Rightarrow$ CONSISTENCY PROBLEM

OUTLOOK

WHAT LIES BEHIND THE CORNER

SUMMARY

ALL GLOBAL FITTING GROUPS HAVE PUBLISHED MAJOR UPDATES FOR LHC RUN II:

- METHODOLOGY AND DATA IMPROVEMENT → IMPROVED AGREEMENT
- TOWARDS A NEW PDF4LHC PRESCRIPTION: COMBINED PDF SETS
- NEW ANALYSIS TOOLS: CMC, META/MC2H AND SM PDFS

GLOBAL FITS: PROGRESS

- MMHT (successor of MSTW08) December 2014
- CT14 June 2015
- for all, progress in methodology & dataset

METHODOLOGY

	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
Tolerance	None	Dynamical	Dynamical
Closure test	✔	✗	✗
Reweighting	replicas	eigenvectors	eigenvectors

- MMHT, CT10 larger # of parms., orthogonal polynomials
- NNPDF closure test

DATASET

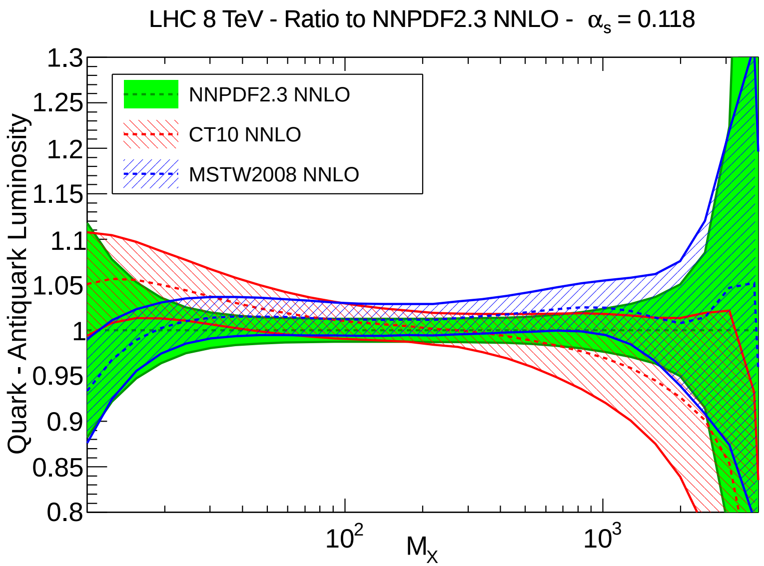
	NNPDF3.0	MMHT14	CT14(PREL)
SLAC P,D DIS	✔	✔	✗
BCDMS P,D DIS	✔	✔	✔
NMC P,D DIS	✔	✔	✔
E665 P,D DIS	✗	✔	✗
CDHSW NU-DIS	✗	✗	✔
CCFR NU-DIS	✗	✔	✔
CHORUS NU-DIS	✔	✔	✗
CCFR DIMUON	✗	✔	✔
NuTeV DIMUON	✔	✔	✔
HERA I NC,CC	✔	✔	✔
HERA I CHARM	✔	✔	✔
H1,ZEUS JETS	✗	✔	✗
H1 HERA II	✔	✗	✗
ZEUS HERA II	✔	✗	✗
E605 & E866 FT DY	✔	✔	✔
CDF & D0 W ASYM	✗	✔	✔
CDF & D0 Z RAP	✔	✔	✔
CDF RUN-II JETS	✔	✔	✔
D0 RUN-II JETS	✗	✔	✔
ATLAS HIGH-MASS DY	✔	✔	✔
CMS 2D DY	✔	✔	✗
ATLAS W,Z RAP	✔	✔	✔
ATLAS W PT	✔	✔	✗
CMS W ASY	✔	✔	✔
CMS W +C	✔	✗	✗
LHCB W,Z RAP	✔	✔	✔
ATLAS JETS	✔	✔	✔
CMS JETS	✔	✔	✔
TTBAR TOT XSEC	✔	✔	✗
TOTAL NLO	4276	2996	3248
TOTAL NNLO	4078	2663	3045

PROGRESS...

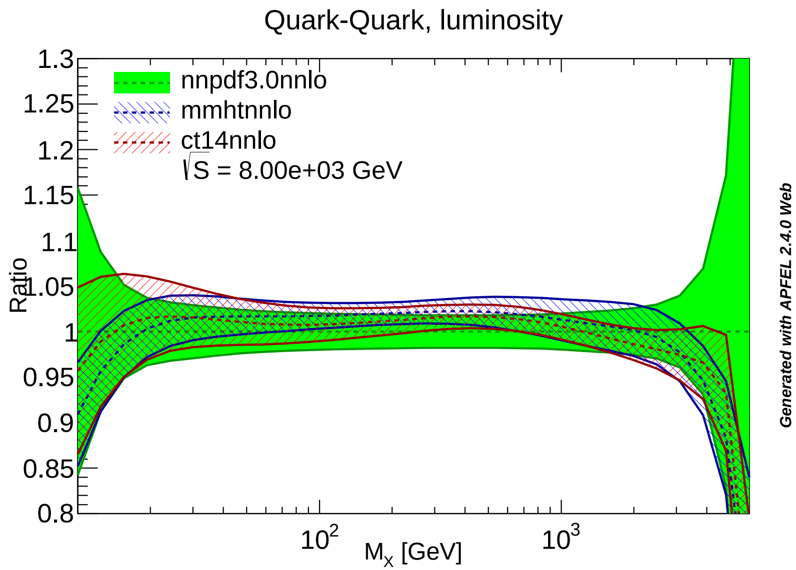
PARTON LUMINOSITIES: IMPROVED AGREEMENT

QUARK-QUARK

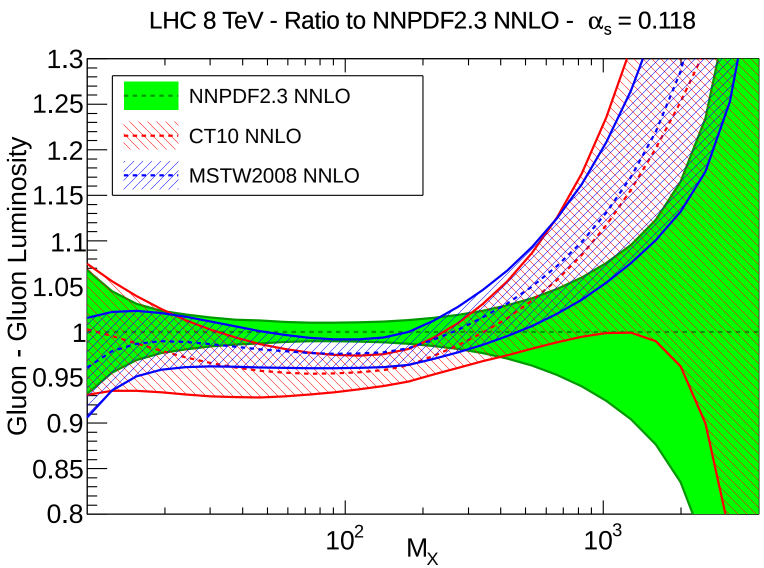
2012

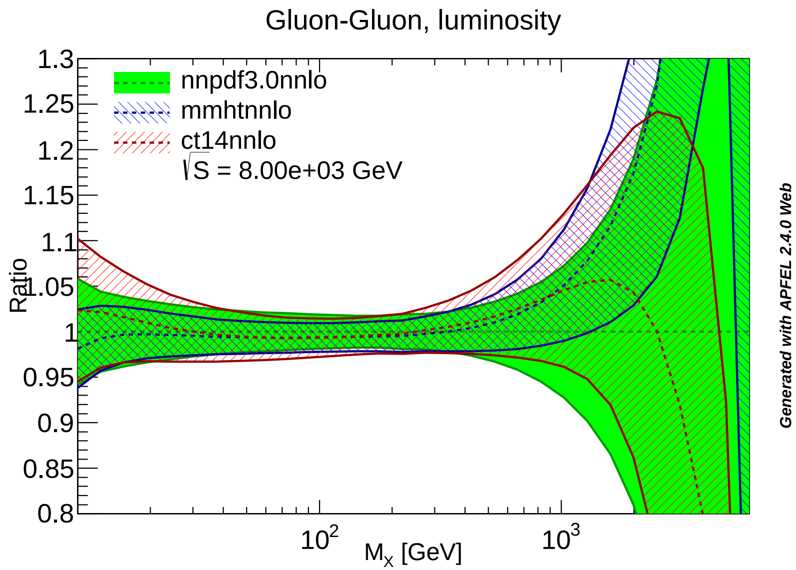


2015



GLUON-GLUON

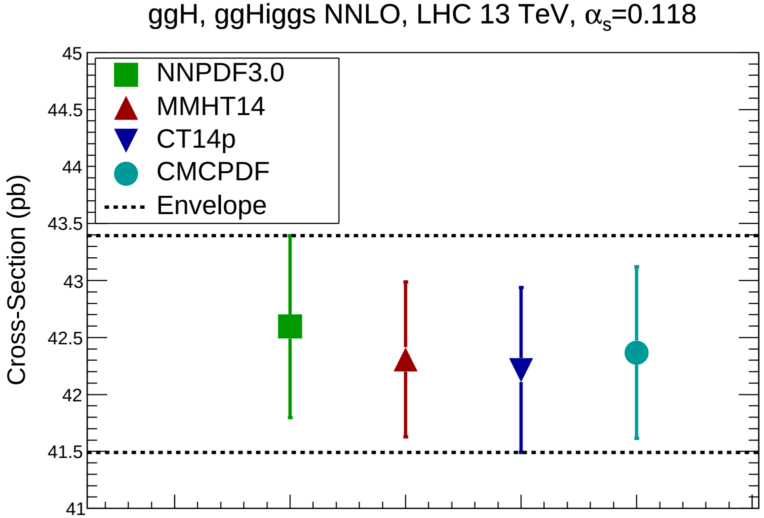




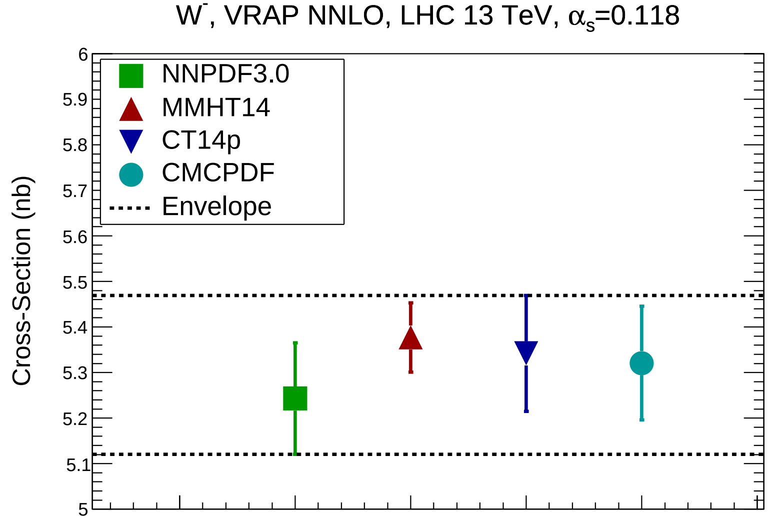
PROGRESS: STANDARD CANDLES & HIGGS

- PDF UNCERTAINTY ON HIGGS PRODUCTION DOWN TO ABOUT 2%
- CONSERVATIVE ENVELOPE NO LONGER NEEDED
- STATISTICAL COMBINATION ADEQUATE

HIGGS IN GLUON FUSION



W^+ PRODUCTION



(Carrazza, Latorre, Rojo, Watt, 2015)

TOWARDS A NEW PDF4LHC PRESCRIPTION

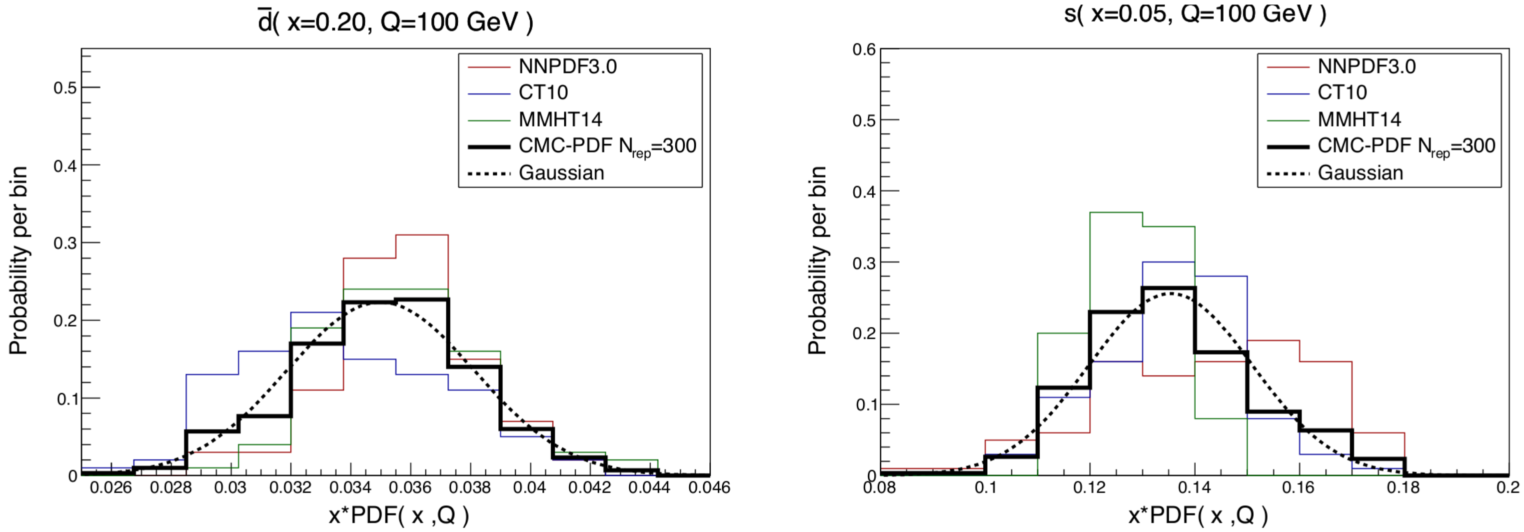
- PERFORM MONTE CARLO COMBINATION OF UNDERLYING PDF SETS
- SETS ENTERING THE COMBINATION MUST SATISFY COMMON REQUIREMENTS
- DELIVER A SINGLE COMBINED PDF SET THROUGH SUITABLE TOOLS

MONTE CARLO COMBINATION

(Watt, S.F., 2010-2013)

- CONVERT ALL SETS INTO MONTE CARLO
- HESSIAN SETS CAN BE CONVERTED BY PERFORMING MONTE CARLO IN PARAMETER SPACE (Watt, Thorne, 2012)
- COMBINE MONTE CARLO REPLICAS INTO SINGLE SET

COMBINED MC SETS FOR ANTIDOWN & STRANGE



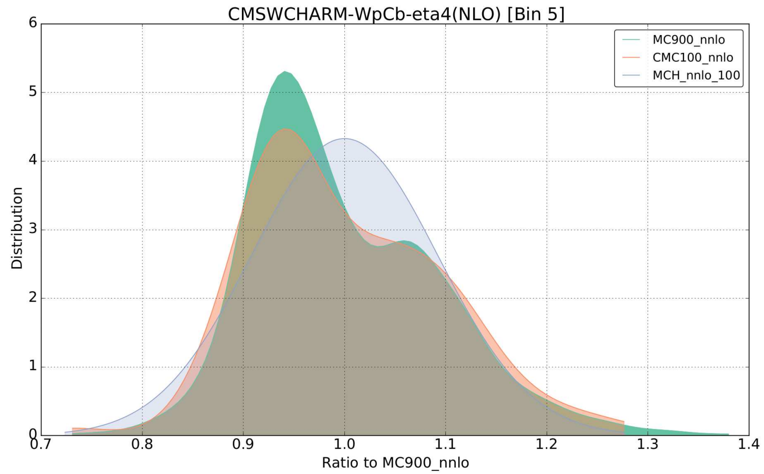
(Carrazza, Latorre, Rojo, Watt, 2015)

CMC PDFs and NONGAUSSIAN BEHAVIOUR

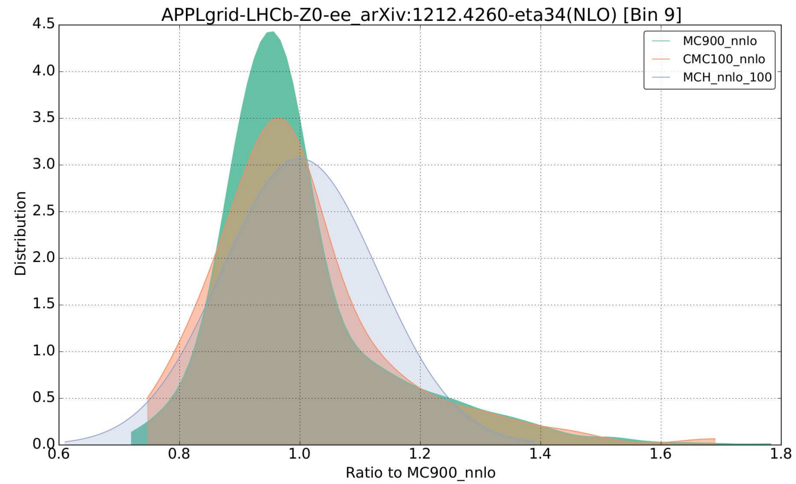
DEVIATION FROM GAUSSIANITY OBSERVED
E.G. AT LARGE x, DUE TO LARGE UNCERTAINTY & POSITIVITY BOUNDS
(MAY BE RELEVANT FOR SEARCHES)

Monte Carlo compared to Hessian

CMS $W + c$ production



LHCb electrons



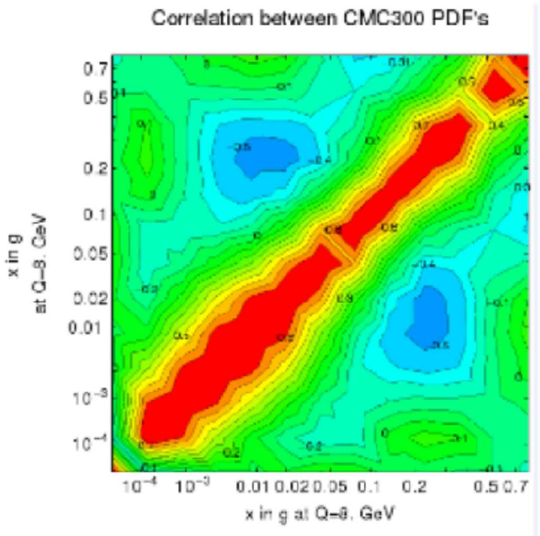
- Monte Carlo PDFs reproduce nongaussian, Hessian fail
- problem does not arise for bulk of data $\Rightarrow$ Hessian adequate!

TOOLS FOR DELIVERY

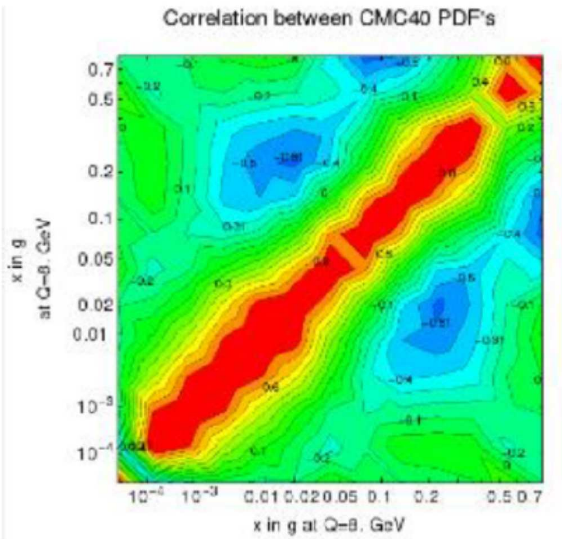
- combined MC set is large (300 replicas)
- Hessian delivery often desirable (PDF uncertainties as nuisance parameters)
- CMC: GA compression of MC set to a smaller set with minimal information loss (300 $\to$ 40 replicas)
- Meta-PDFs or MC-H PDFs: Hessian representation obtained by refitting MC replicas with functional form (Meta), or representing them on linear basis of replicas (MC-H)
- validation and benchmarking succesful

gluon-gluon correlation

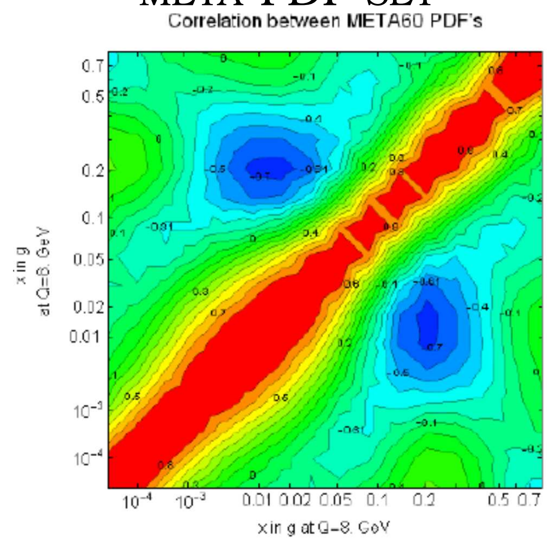
starting combined set



compressed MC set



meta-PDF set



(PDF4LHC: preliminary, 2015)

THE MC2H IDEA:

- NONGAUSSIAN EFFECTS NOT VERY IMPORTANT FOR BULK OF DATA
- HESSIAN DELIVERY OFTEN ADVANTAGEOUS FOR ANALYSIS
- CAN WE CONVERT MC TO HESSIAN (GAUSSIAN)?

A: USE REPLICAS AS BASIS FUNCTIONS (CONTINUITY, SUM RULES, DGLAP AUTOMATICALLY IMPLEMENTED)

(Carrazza, S.F., Rojo, Kassabov 2015)

MC2H-GA

- SINGLE OUT GAUSSIAN REGION (ONE SIGMA = 68% C.L.)
- OPTIMIZE UNCERTAINTIES VIA GENETIC ALGORITHM

MC2H-PCA

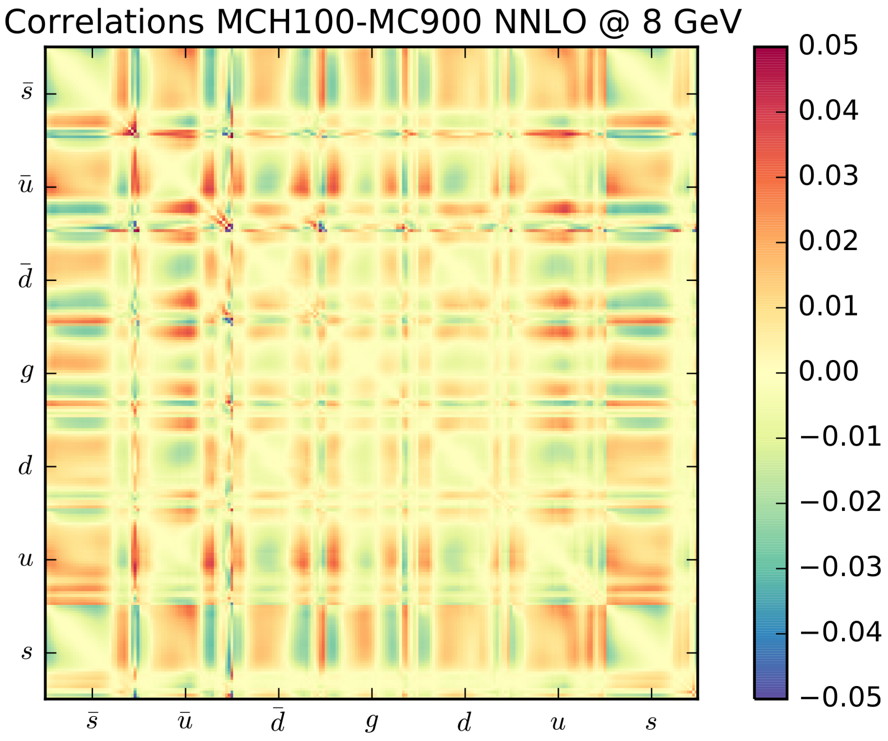
- REPRODUCE COVARIANCE MATRIX ON VERY FINE SET OF GRID POINTS
- REPRESENT IT BY SINGULAR-VALUE DECOMPOSITION ON REPLICAS
- PICK LARGEST CONTRIBUTIONS (PRINCIPAL COMPONENT ANALYSIS)

$\Rightarrow$ COVARIANCE MATRIX PERFECTLY REPRODUCED; NO CHOICES: NO BIAS

MC2H-PCA

- PRIOR COMBINATION OF CT14, MMHT, NNPDF3.0: MC900 OR META300
- MC2H=PCA: SETS OF 100 OR 120 HESSIAN EIGENVECTORS
- META-PDFS: V2 SETS OF 2*30 AND 2*50 EIGENVECTORS

THE CORRELATION MATRIX:
PRIOR-FINAL (HIGH RESOLUTION)
MC2H

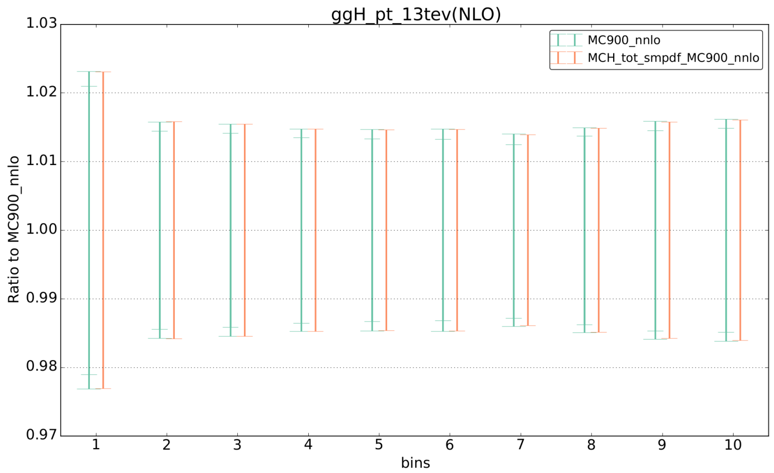


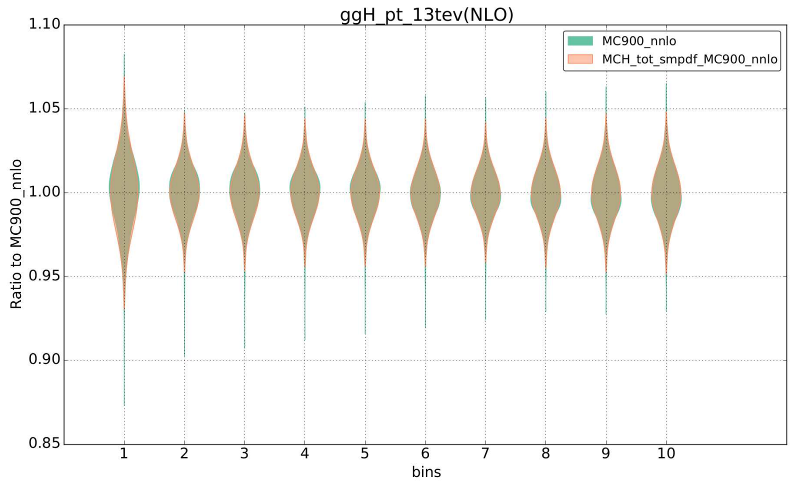
MC2H ACHIEVES PERCENT ACCURACY

MINIMAL SETS: SM-PDFS

- GIVEN ONE OR MORE PROCESSS ("SIGNAL"), SELECT EIGENVECTORS WHICH PROVIDE THE DOMINANT CONTRIBUTION:
  - DETERMINE SUBSET OF GRID POINTS WHICH HAVE THE HIGHEST CORRELATION TO THE PROCESS
  - PERFORM PCA ANALYSIS ON THE CORRESPONDING SUBMATRIX
  - NOTE USAGE OF SUBGRID GUARANTEES STABILITY: SIMILAR PROCESSES WILL ALSO BE WELL REPRODUCED (EXAMPLE: TOP VS HIGGS)
- .
- .

HIGGS
13 eigenvectors
HIGGS p_T DISTRIBUTION IN GLUON FUSION

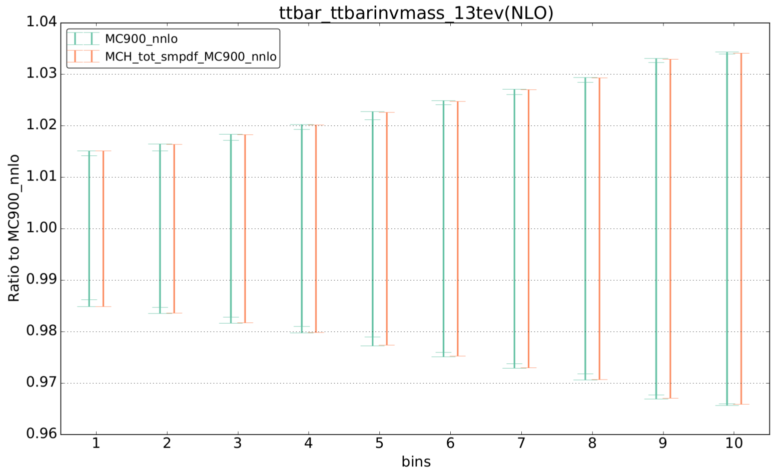


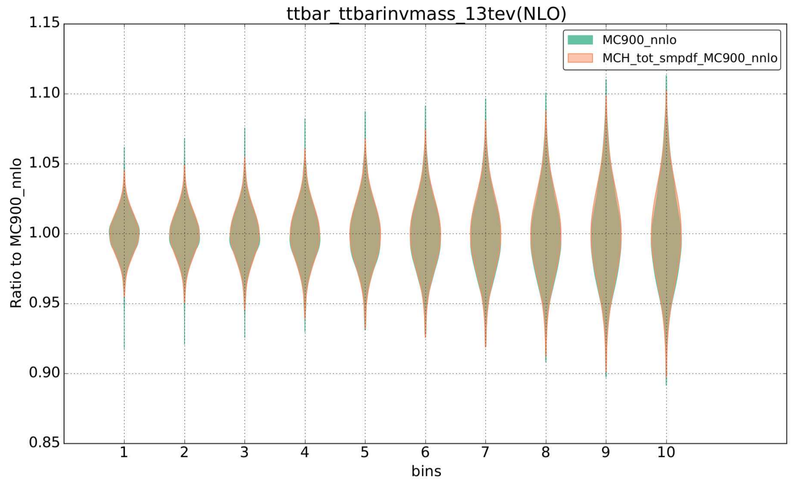


MINIMAL SETS: SM-PDFS

- GIVEN ONE OR MORE PROCESSS ("SIGNAL"), SELECT EIGENVECTORS WHICH PROVIDE THE DOMINANT CONTRIBUTION:
  - DETERMINE SUBSET OF GRID POINTS WHICH HAVE THE HIGHEST CORRELATION TO THE PROCESS
  - PERFORM PCA ANALYSIS ON THE CORRESPONDING SUBMATRIX
  - NOTE USAGE OF SUBGRID GUARANTEES STABILITY: SIMILAR PROCESSES WILL ALSO BE WELL REPRODUCED (EXAMPLE: TOP VS HIGGS)
- ADD ONE OR MORE PROCESSES ("BACKGROUND"): REPEAT ANALYSIS & PICK FURTHER EIGENVECTORS
- .

HIGGS+TOP
14 eigenvectors
TOP INVARIANT MASS DISTRIBUTION

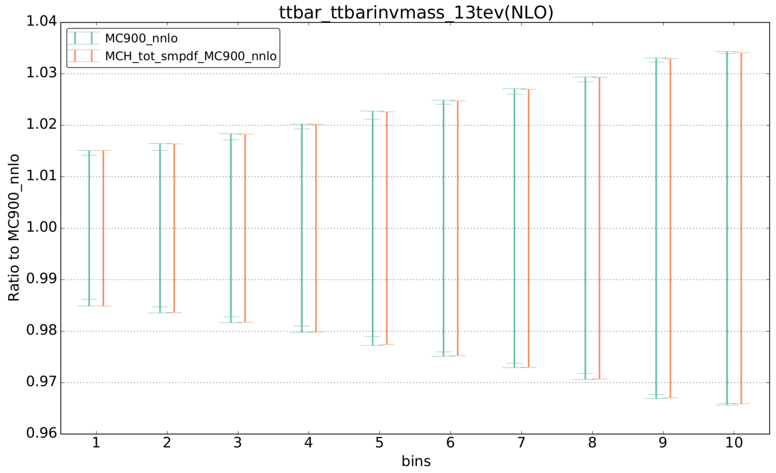


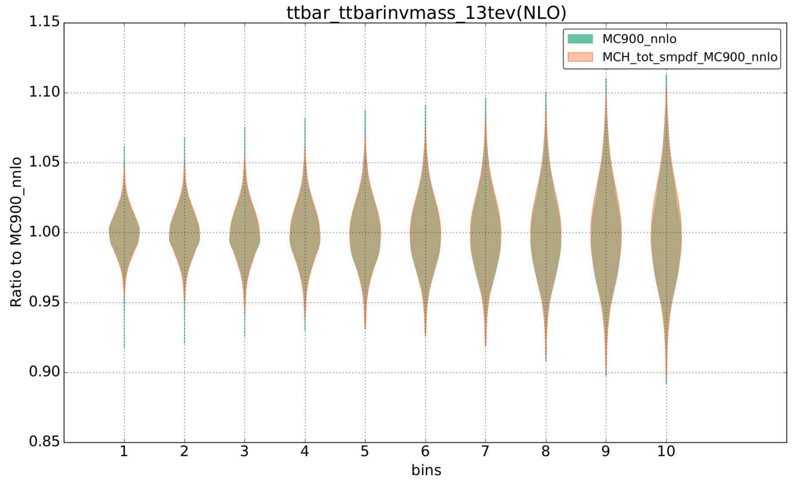


MINIMAL SETS: SM-PDFS

- GIVEN ONE OR MORE PROCESSS ("SIGNAL"), SELECT EIGENVECTORS WHICH PROVIDE THE DOMINANT CONTRIBUTION:
  - DETERMINE SUBSET OF GRID POINTS WHICH HAVE THE HIGHEST CORRELATION TO THE PROCESS
  - PERFORM PCA ANALYSIS ON THE CORRESPONDING SUBMATRIX
  - NOTE USAGE OF SUBGRID GUARANTEES STABILITY: SIMILAR PROCESSES WILL ALSO BE WELL REPRODUCED (EXAMPLE: TOP VS HIGGS)
- ADD ONE OR MORE PROCESSES ("BACKGROUND"): REPEAT ANALYSIS & PICK FURTHER EIGENVECTORS
- CAN ITERATE AT WILL $\Rightarrow$ EVENTUALLY RECOVER FULL EIGENVECTOR SET

HIGGS+TOP+Z+W
15 eigenvectors
W p_T DISTRIBUTION





OUTLOOK: NNPDF3.1

NEW DATA (MINIMAL SET)

- HERA-II COMBINED DATA `arxiv:1506.06042`
- D0 W ASYMMETRY `arXiv:1412.2862`
- ATLAS LOW-MASS DY `arXiv:1404.1212`
- ATLAS PROMPT PHOTON `arXiv:1311.1440`
- ATLAS $W + c$ `arXiv:1402.6263`
- ATLAS Z p_t `arXiv:1406.3660`
- ATLAS $t\bar{t}$ RAPIDITY `arXiv:1407.0371`
- ATLAS INCLUSIVE JETS 7 TEV 5 FB^{-1} `arXiv:1410.8857`
- CMS DOUBLE-DIFFERENTIAL 8 TEV `arXiv:1412.1115`
- CMS Z p_t `arXiv:1504.03511`
- LHCB $W \to \mu\nu$ RAP. `arxiv:1408.4354`

NNPDF3.1 AND BEYOND

- RESUMMED PDFS
  - SMALL x AND EVOLUTION
  - THRESHOLD RESUMMATION AND NEW PHYSICS SEARCHES
- HEAVY QUARKS
  - RUNNING QUARK MASSES & QUARK MASS STUDIES
  - FITTED ("INTRISIC") CHARM
- THEORY UNCERTAINTY ON PDFS
  - SCALE VARIATION
  - PERTURBATIVE SERIES: CACCIARI-HOUDEAU
- MORE CLOSURE TESTS:
  - INCONSISTENT DATA
  - QUANTITATIVE MODELS OF FUNCTIONAL UNCERTAINTY
  - TOLERANCE & $\Delta\chi^2$ RULE
- QED PDF SET
  - MIXED QCD-QED EFFECTS
  - DETERMINATION OF PHOTON FROM WW PRODUCTION
- MONTE CARLO PDFS

PDFs: PLUMBING OR PRECISION PHYSICS?

EXTRAS

TREATMENT OF α_s
NEW SIMPLIFIED PDF4LHC PRESCRIPTION

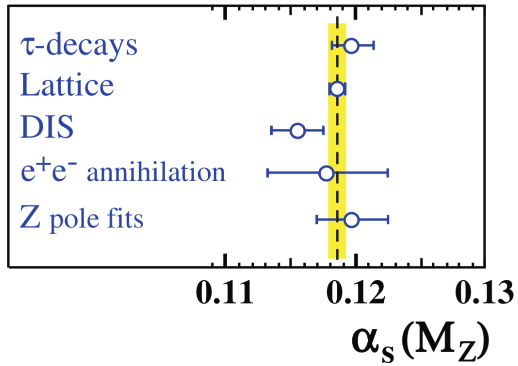
- SEPARATE α_s UNCERTAINTY FROM PDF UNCERTAINTY:
  DETERMINE EACH SEPARATELY AND COMBINE IN QUADRATURE IF NEEDED
  PROVEN TO BE EQUIVALENT TO CORRELATED DETERMINATION, UP TO NONLINEAR TERMS
- AGREE ON A CENTRAL VALUE AND AN UNCERTAINTY ON α_s (SEE BELOW)
- FOR THE DETERMINATION OF THE PDF UNCERTAINTY,
  USE PDFS AT THE (FIXED) CENTRAL VALUE OF α_s
- FOR THE DETERMINATION OF THE α_s UNCERTAINTY,
  - COMPUTE OBSERVABLES WITH α_s SHIFTED BY ONE σ, WITH PDFS CORRESPONDING TO THE GIVEN FIXED VALUE
  - TAKE RESULT AS ONE-σ α_s UNCERTAINTY ON OBSERVABLE

THE VALUE OF α_s

PDG VALUE (AUGUST 2014): $\alpha_s(M_Z) = 0.1185 \pm 0.0006$

COMMENTS

- LATTICE UNCERTAINTY CURRENTLY ESTIMATED BY FLAG (arXiv:1310.8555) TO BE TWICE THE PDG VALUE (± 0.0012)
- IT IS AN AN AVERAGE OF AVERAGES
- SOME SUB-AVERAGES (E.G. DIS) INCLUDE MUTUALLY INCONSISTENT/INCOMPATIBLE DATA/EXTRACTIONS



- SOME SUB-AVERAGES (E.G. τ OR JETS) INCLUDE DETERMINATIONS WHICH DIFFER FROM EACH OTHER BY EVEN FOUR-FIVE σ
- AVERAGING THE TWO MOST RELIABLE VALUES (GLOBAL EW FIT & τ, BOTH N^3LO, NO DEP. ON HADRON STRUCTURE) GIVES

$$\alpha_s = 0.1196 \pm 0.0010$$

NEW PDF4LHC AGREEMENT

- PDG UNCERTAINTY CONSERVATIVELY MULTIPLIED BY 2
- CENTRAL VALUE & UNCERTAINTY ROUNDED:
  PDF SETS USUALLY GIVEN IN STEPS OF $\Delta\alpha_s(M_z) = 0.001$

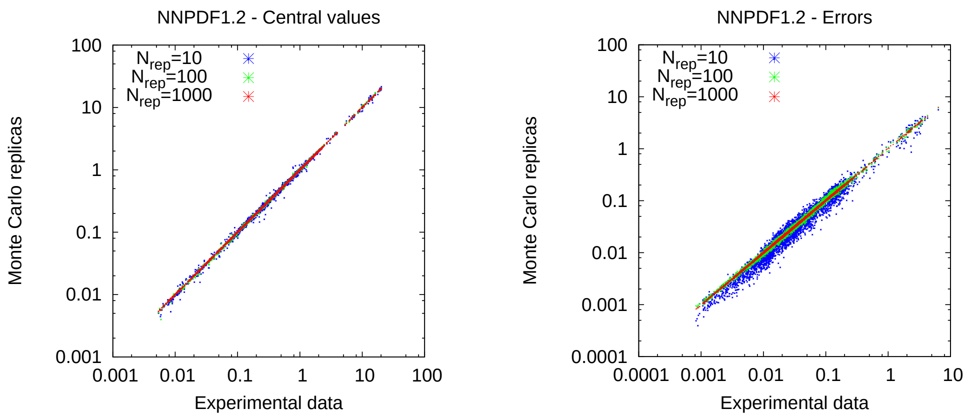
$$\alpha_s(M_Z) = 0.118 \pm 0.001$$

THE NNPDF APPROACH:
THE NEURAL MONTE CARLO

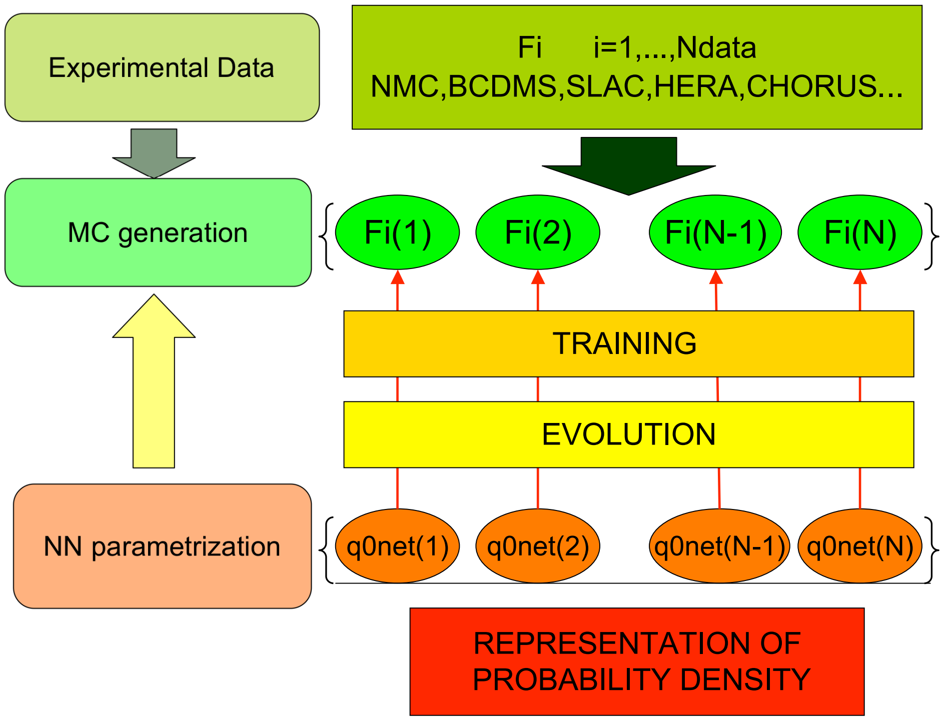
BASIC IDEA: MONTE CARLO SAMPLING OF THE PROBABILITY MEASURE IN THE (FUNCTION) SPACE OF PDFs

- START FROM MONTE CARLO SAMPLING OF DATA SPACE
- SPACE OF FUNCTIONS HUGE
  5 BINS FOR 10 PTS$\times$ 7 FCTNS $\to 5^{70} \sim 10^{49}$ BINS
- IMPORTANCE SAMPLING: DATA TELL US WHICH BINS ARE POPULATED

replica averages vs. central values — replica standard dev. vs. uncertainties

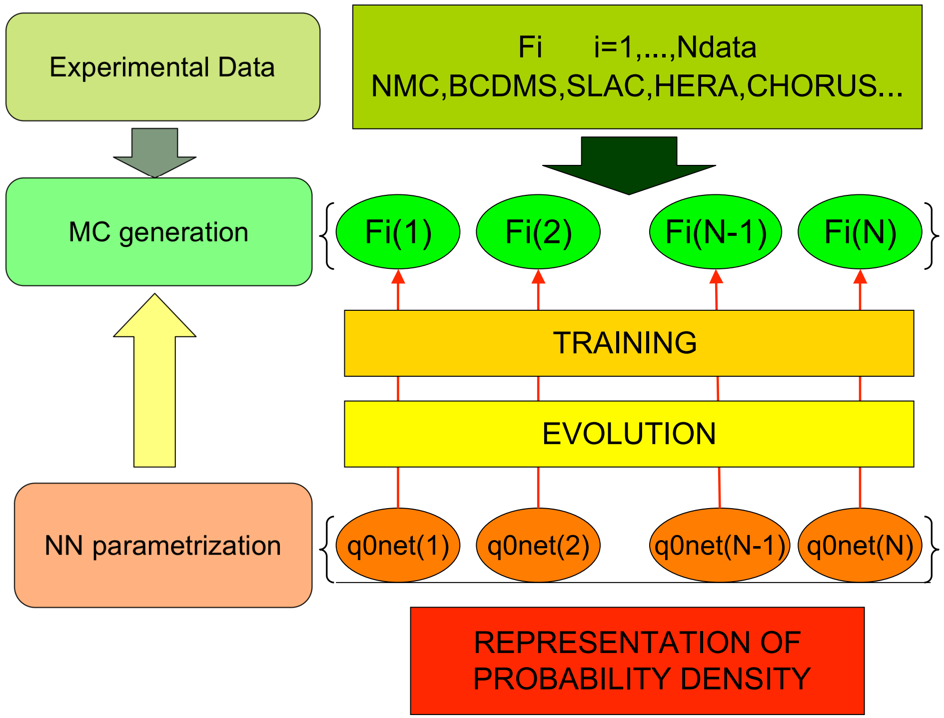


10 REPLICAS ENOUGH FOR CENTRAL VALS, 100 FOR UNCERTAINTIES, 1000 FOR CORRELNS



DATA MONTE CARLO ⇒ PDF MONTE CARLO
NEURAL NETWORK PARM+ CROSS-VALIDATION METHOD

- EACH PDF↔ NEURAL NETWORK PARAMETRIZED BY 37 PARAMETERS
- NNPDF1.2: $37 \otimes 7 = 259$ PARMS (RECALL MSTW, CTEQ → 20 FREE PARAMETERS)
  "INFINITE" NUMBER OF PARAMETERS⇒ CAN REPRESENT ANY FUNCTION
- COMPLEX SHAPES (LARGE NO.OF PARAMETERS) REQUIRE LONGER FITTING
- FIT STOPS WHEN QUALITY OF FIT TO RANDOMLY SELECTED "VALIDATION" DATA (NOT FITTED) STOPS IMPROVING
- CAN OBTAIN A FIT WITH χ^2 LOWER THAN BEST FIT ("OVERLEARNING")

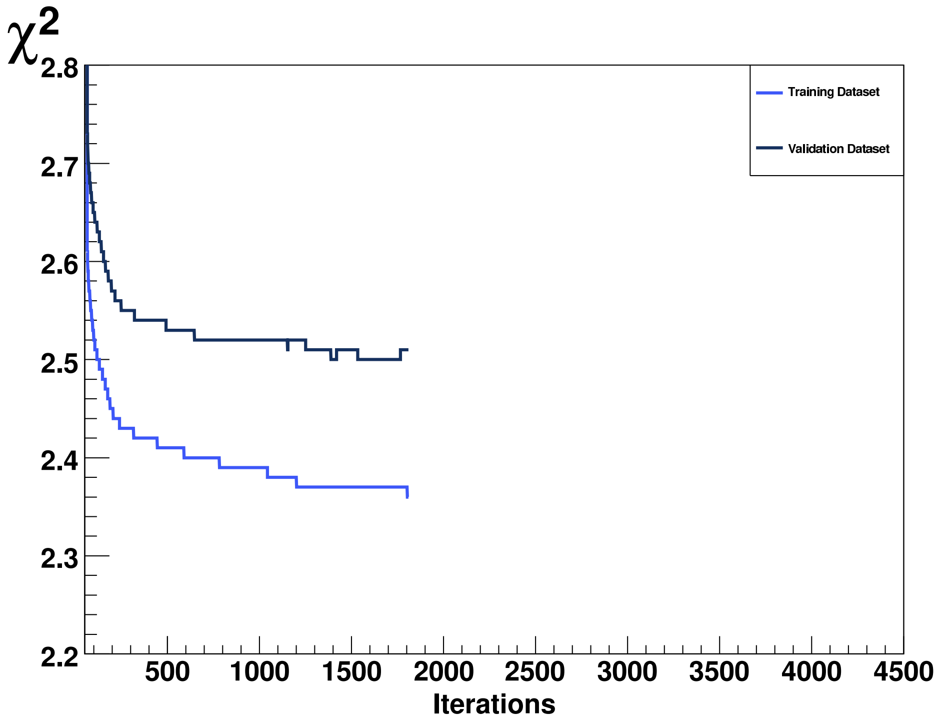


DATA MONTE CARLO ⇒ PDF MONTE CARLO
CROSS-VALIDATION

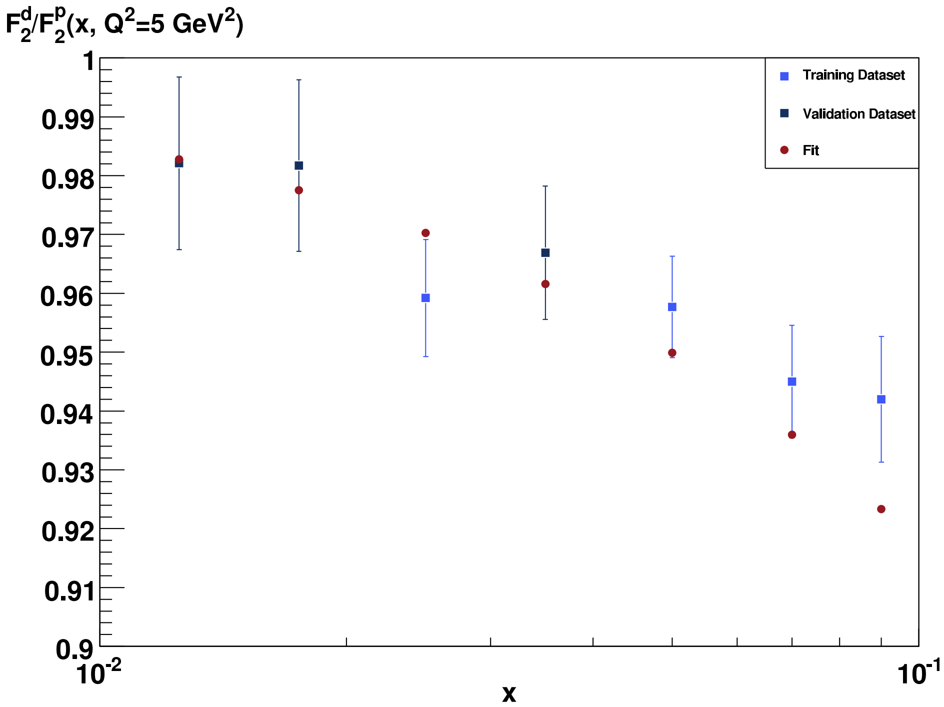
- REPLICAS ARE FITTED TO A DATA SUBSET
- A DIFFERENT SUBSET OF DATA USE FOR EACH REPLICA
- OPTIMAL FIT WHEN FIT TO VALIDATION (CONTROL) DATA STOPS IMPROVING
-

OPTIMAL FITTING

χ^2



FIT TO DATA

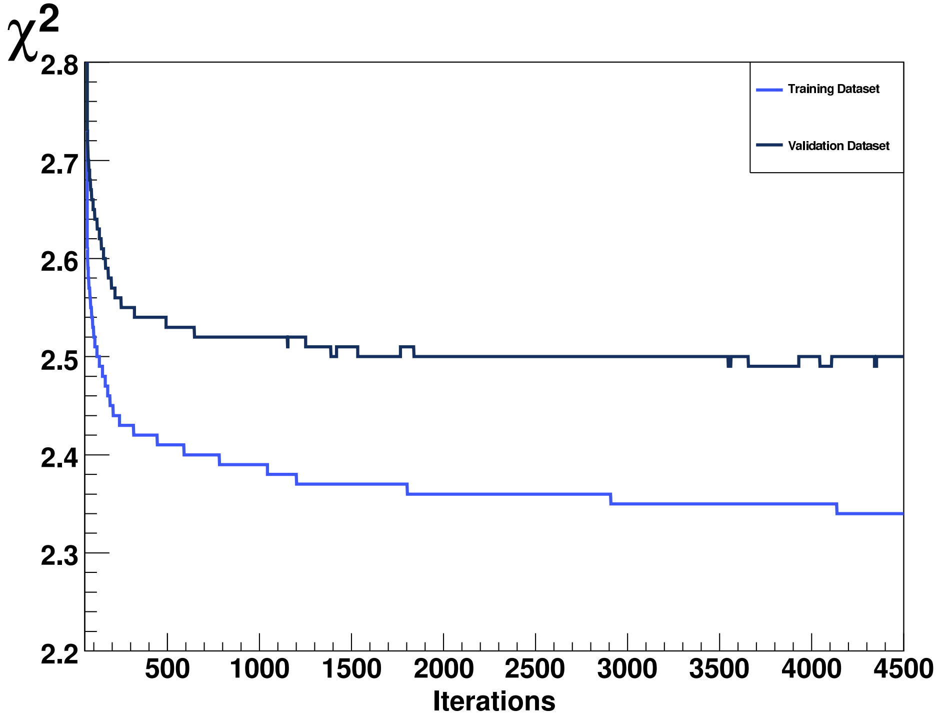


DATA MONTE CARLO ⇒ PDF MONTE CARLO
CROSS-VALIDATION

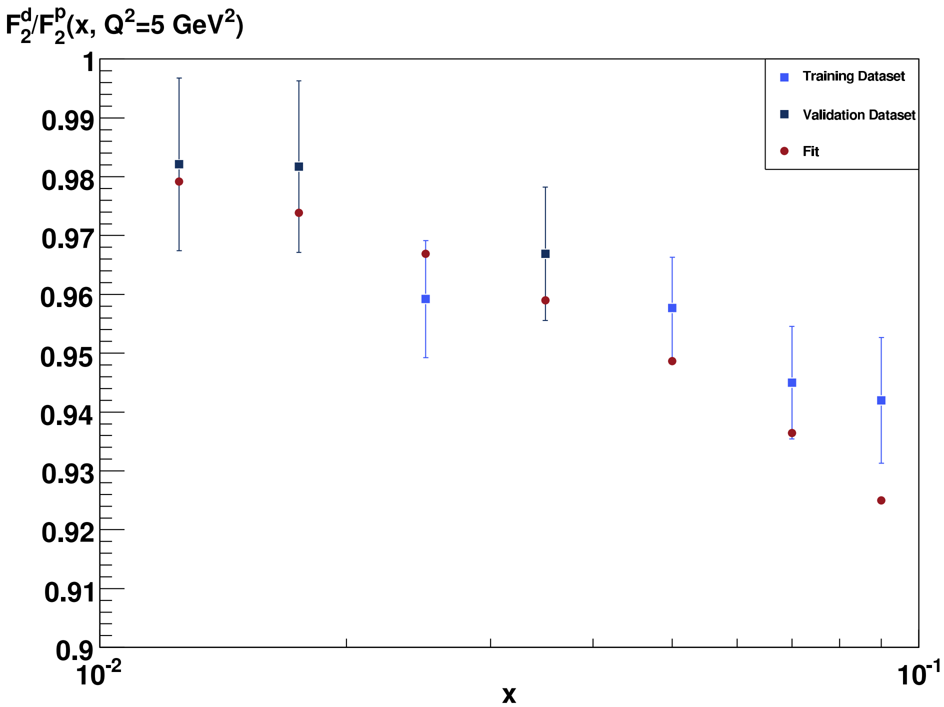
- REPLICAS ARE FITTED TO A DATA SUBSET
- A DIFFERENT SUBSET OF DATA USE FOR EACH REPLICA
- OPTIMAL FIT WHEN FIT TO VALIDATION (CONTROL) DATA STOPS IMPROVING
- THE BEST FIT IS NOT AT THE MINIMUM OF THE χ^2

OVERFITTING

χ^2



FIT TO DATA



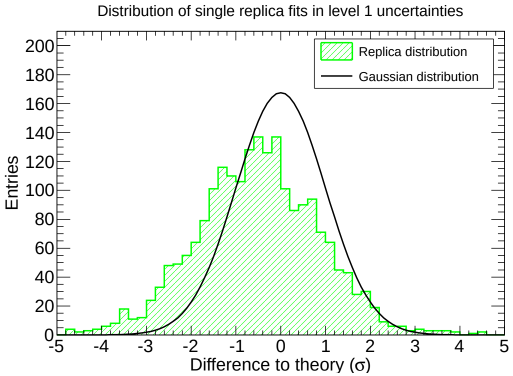
LOOKBACK CROSS-VALIDATION

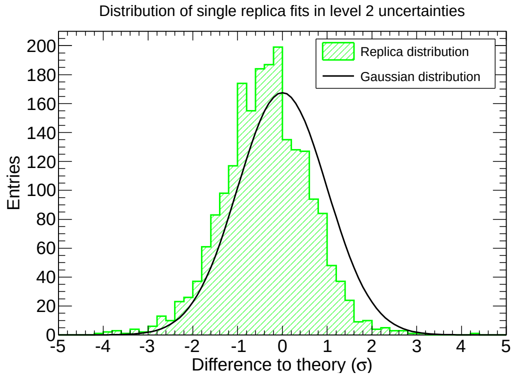
- IN PREVIOUS NNPDF RELEASES, "INCREASING" AND "DECREASING" TRAINING AND VALIDATION χ^2 DEFINED IN TERMS OF THRESHOLD VALUES δ_{tr} AND δ_{val}:
  INCREASE: $\chi^2_{val}(N_{gen}+\Delta) > \chi^2(N_{gen}+\Delta)+\delta_{val}$
- IN NNPDF3.0 USE LOOKBACK:
  FIT IS RUN UP TO SOME LARGE # OF GA GENERATIONS
  THEN ONE "LOOKS BACK" FOR ABSOLUTE MIN. OF VALIDATION χ^2
- CHECK THAT RESULTS ARE INDEPENDENT OF THE LARGE # OF GA GENS
- CHECK THAT RESULTS ARE INDEPENDENT OF FLUCTUATIONS IN VALUE OF ABSOLUTE MINIMUM
  DIFFERENT STOPPING POINTS, BUT INDISTINGUISHABLE PDFs

LEVEL 1 vs. LEVEL 2

DO WE NEED THE PSEUDODATA REPLICAS?

TRUTH-FIT: LEVEL 1 VS. LEVEL 2

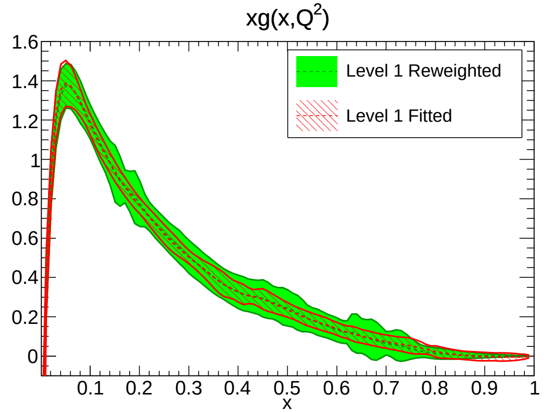


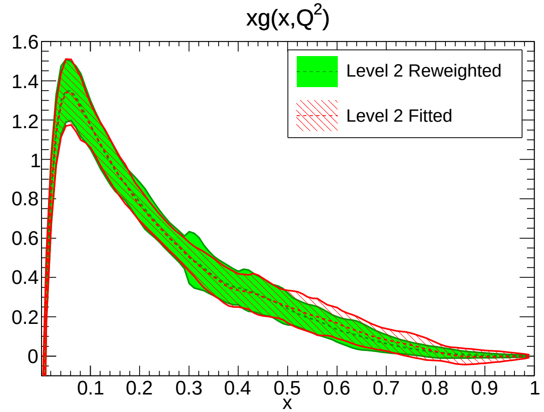


- LEVEL 1 UNDERESTIMATES UNCERTAINTIES
- LEVEL 0 TRUTH-FIT DISTN. WIDER THAN PREDICTED
- REWEIGHT VS. REFIT: X STAT. EQUIVALENCE FOR LEVEL 2
- REWEIGHT VS. REFIT: REFITTED SIGMA TOO SMALL FOR LEVEL 1

REWEIGHT VS REFIT:

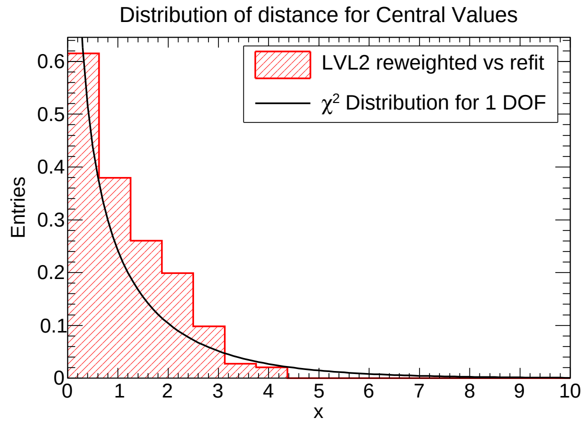
LEVEL 1 VS. LEVEL 2



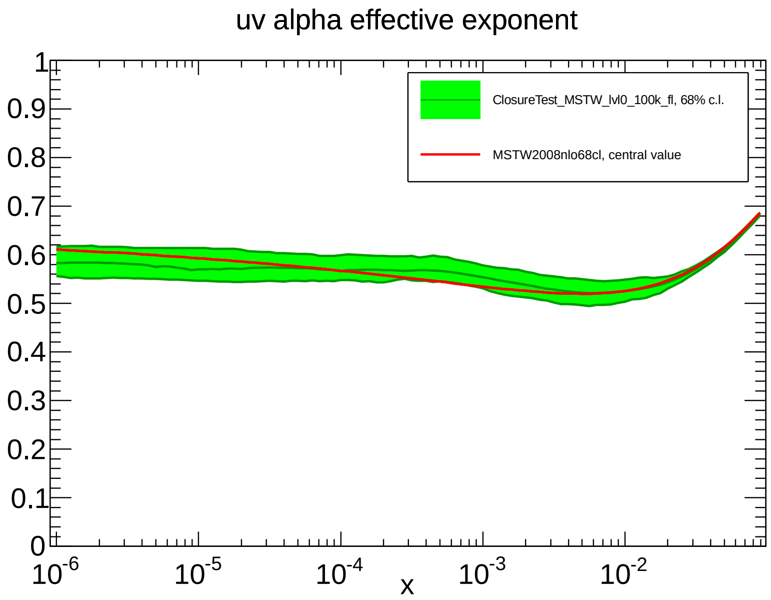


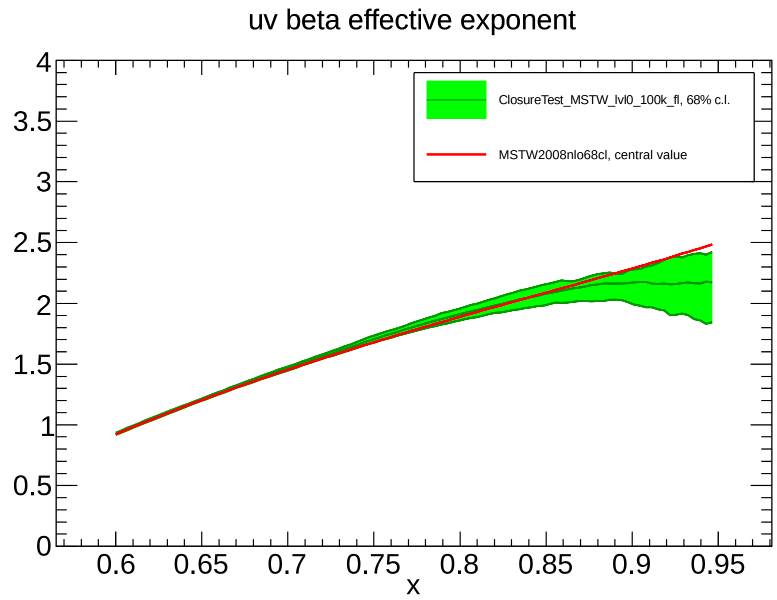
REWEIGHT-REFIT

(LEVEL 2)



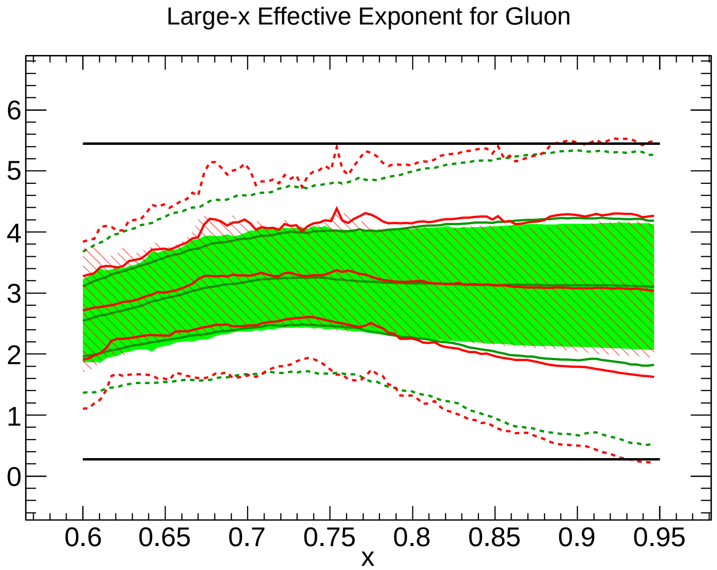
ASYMPTOTIC EXPONENTS
LEVEL 0 TEST

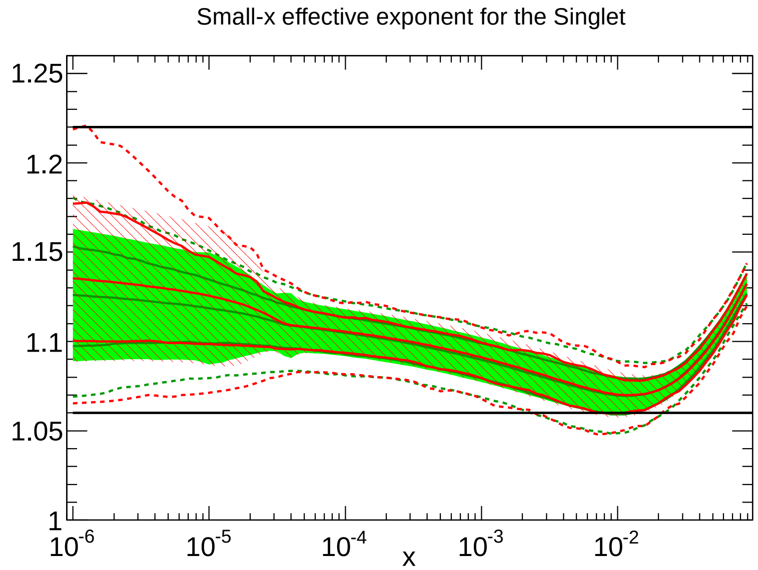




- AS $x \to 0$, PDF GOES AS x^{α}, AS $x \to 1$, PDF GOES AS $(1-x)^{\beta}$
- DEFINE EFFECTIVE EXPONENTS $\alpha_{\mathrm{eff},i}(x) \equiv \frac{\ln f_i(x)}{\ln 1/x}$, $\beta_{\mathrm{eff},i}(x) \equiv \frac{\ln f_i(x)}{\ln(1-x)}$
- COMPARE VALUES FROM FIT WITH VALUES OBTAINED FROM UNDERLYING “TRUE” (MSTW08) FORM

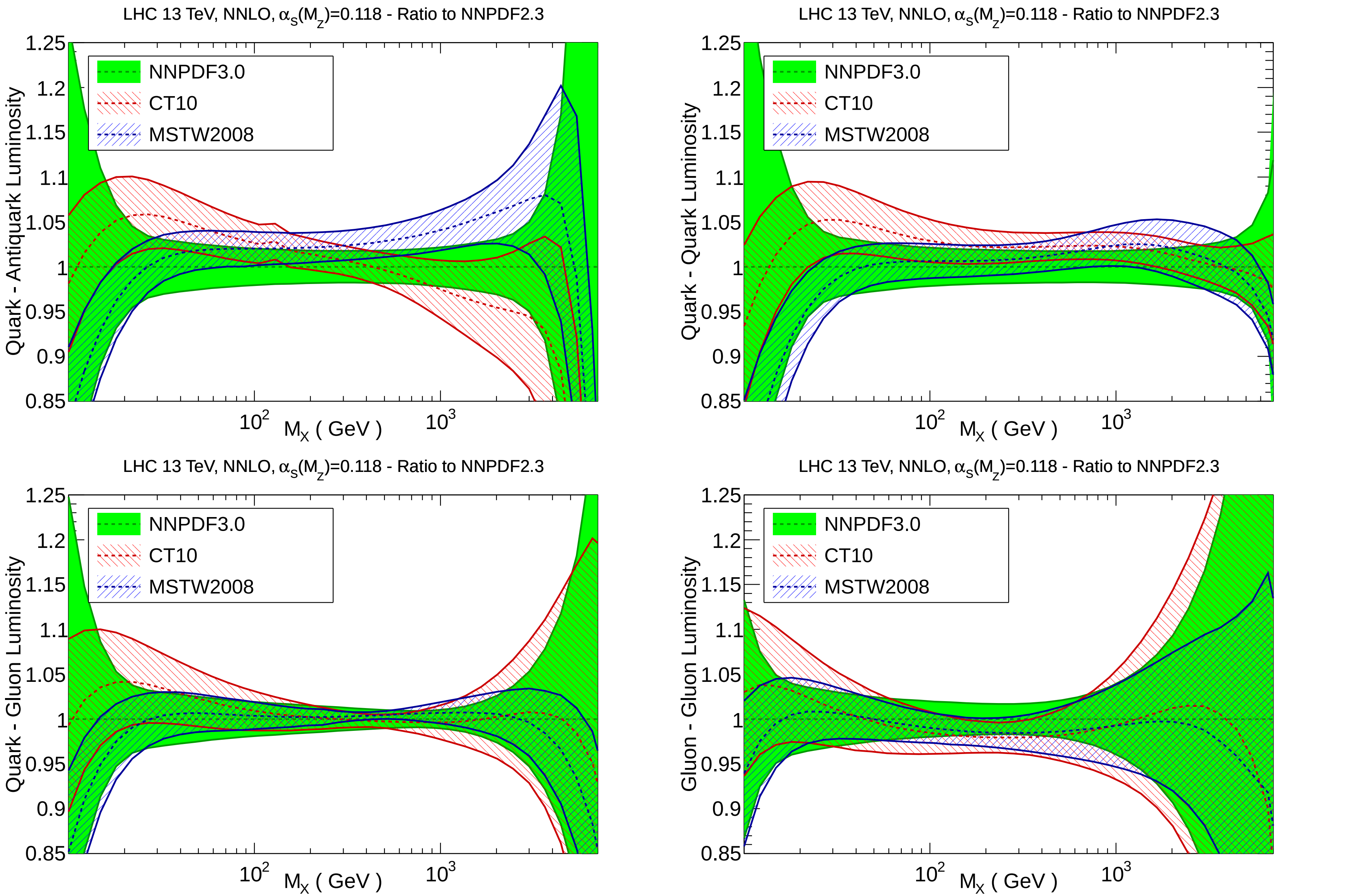
PREPROCESSING



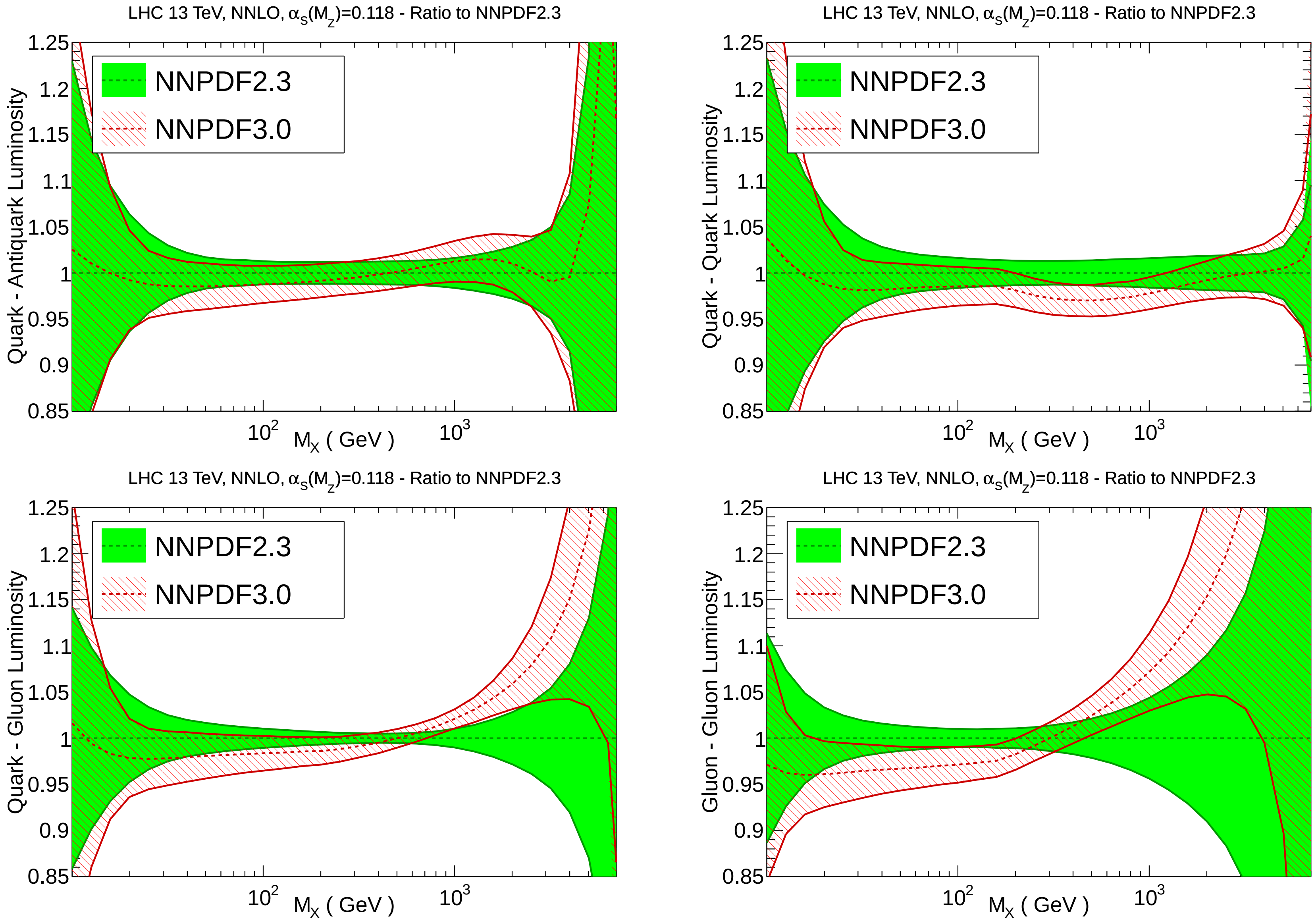


- PDFs ARE PARAMETRIZED WITH NEURAL NETWORKS TIMES PREPROCESSING FUNCTION: $f_i(x) = x^{\alpha_i}(1-x)^{\beta_i} NN(x)$
- GOAL IS TO SPEED UP TRAINING WITHOUT BIASING RESULT
- α_i, β_i RANDOM REPLICA BY REPLICA WITH UNIFORM DISTRIBUTION IN RANGE
- CHECK THAT THE RANGE IS WIDER THAN THE 90% C.L. OF EFFECTIVE EXPONENTS

NNPDF3.0 vs CT10 & MSTW08
PARTON LUMINOSITIES



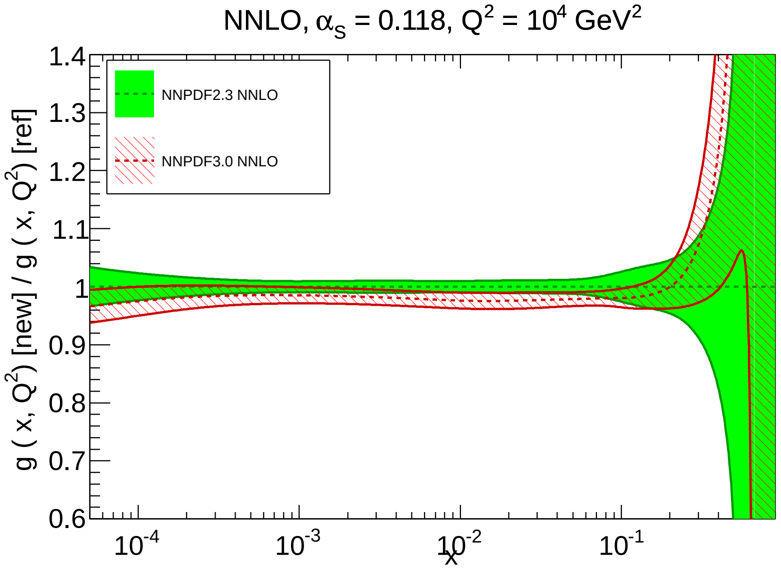
NNPDF2.3 vs NNPDF3.0
PARTON LUMINOSITIES

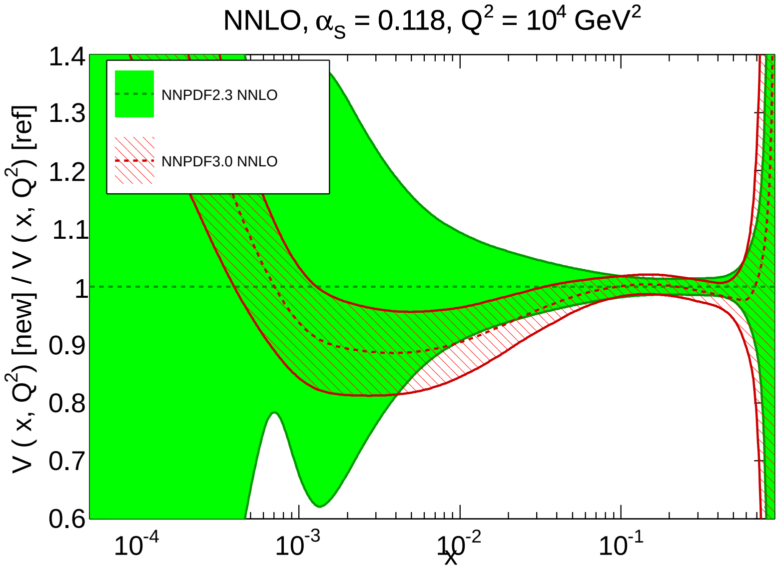


NNPDF2.3 vs NNPDF3.0

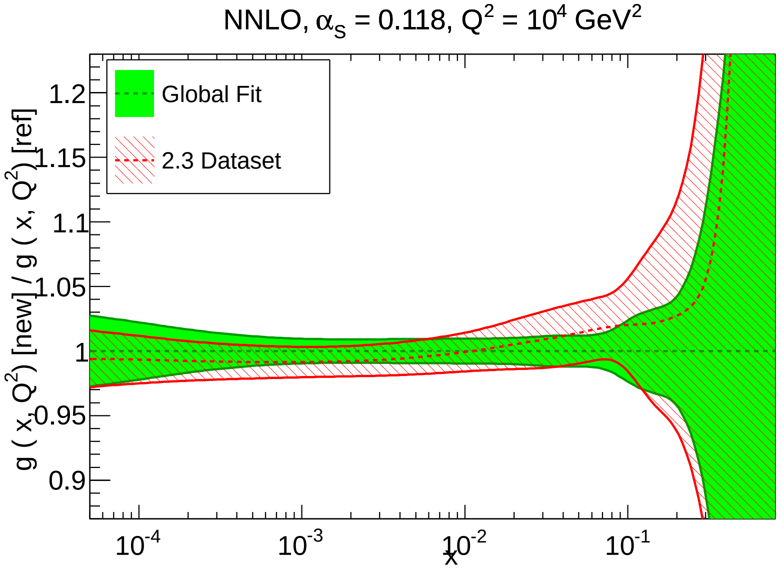
Methodology vs. Data

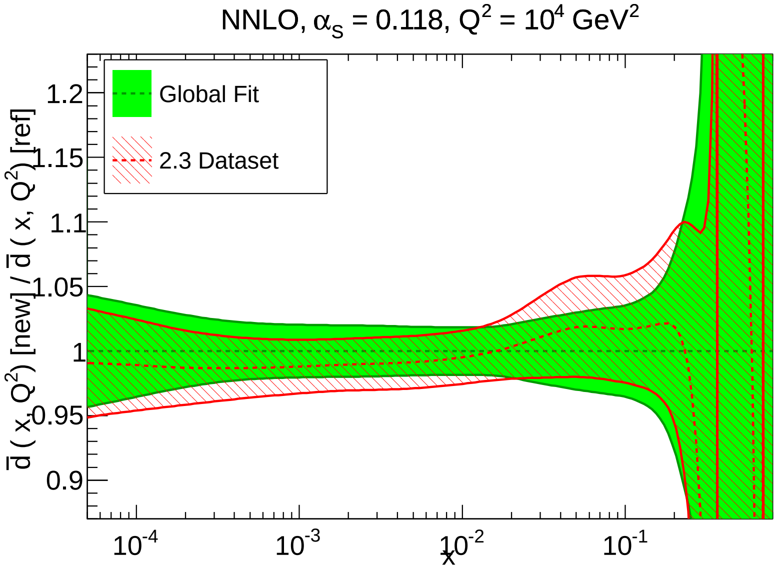
NNLO 2.3 vs 3.0: gluon & valence





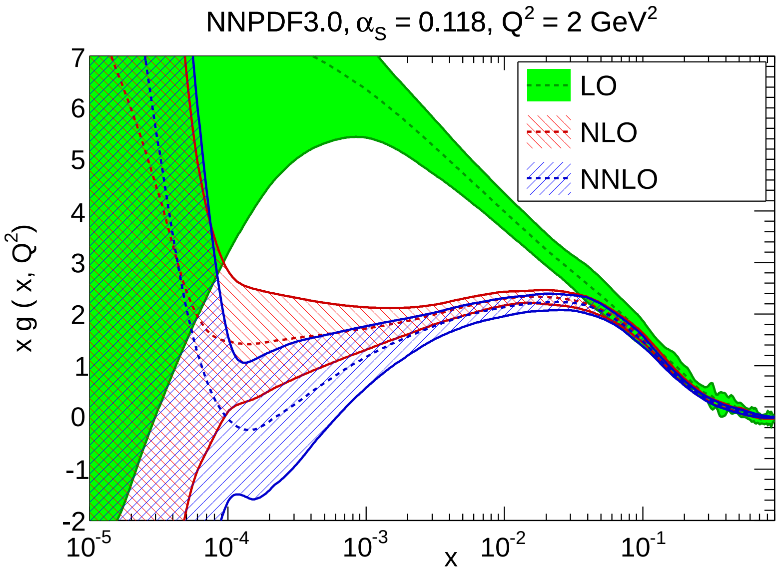
3.0 default vs 2.3-like dataset: gluon & antidown

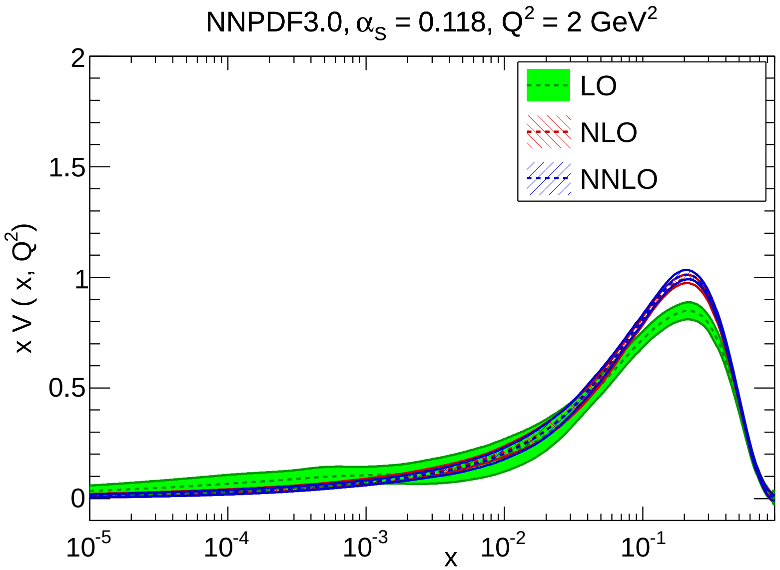




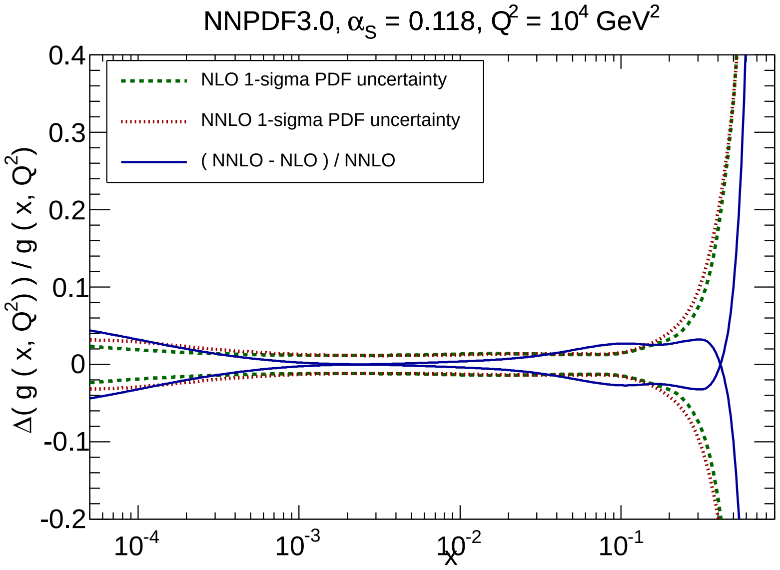
PERTURBATIVE STABILITY

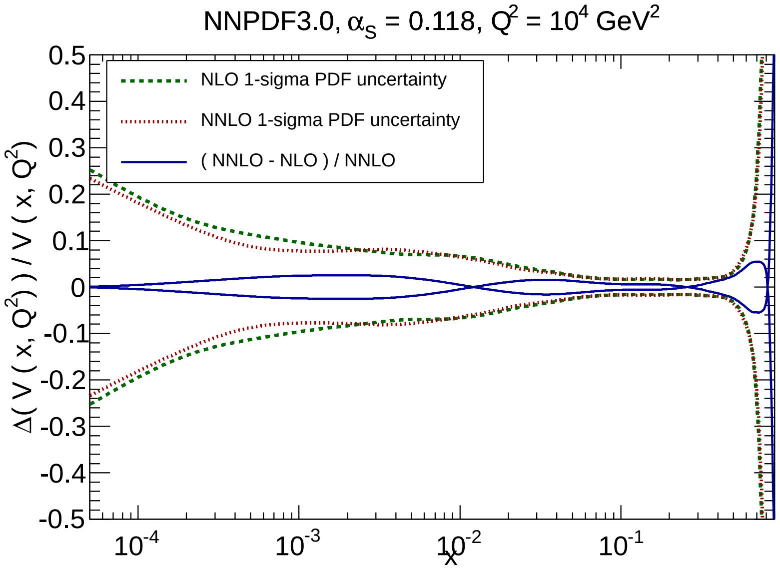
LO, NLO, NNLO: GLUON & VALENCE



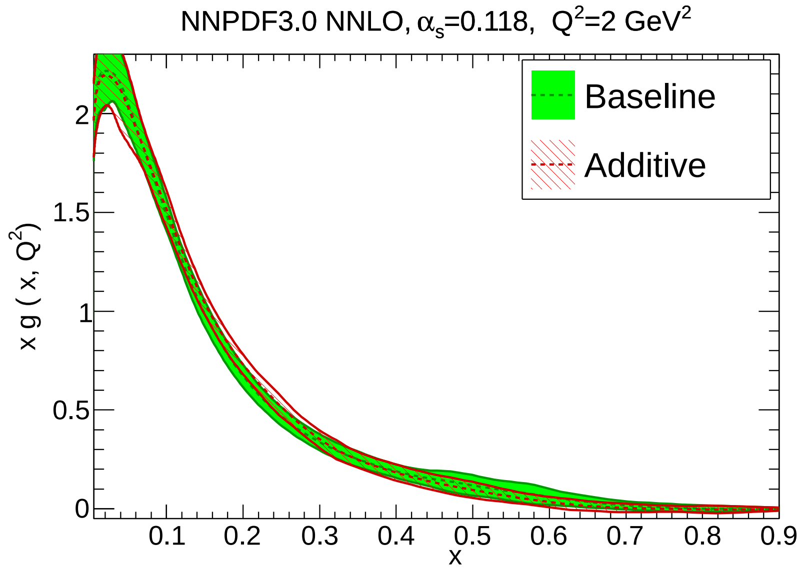


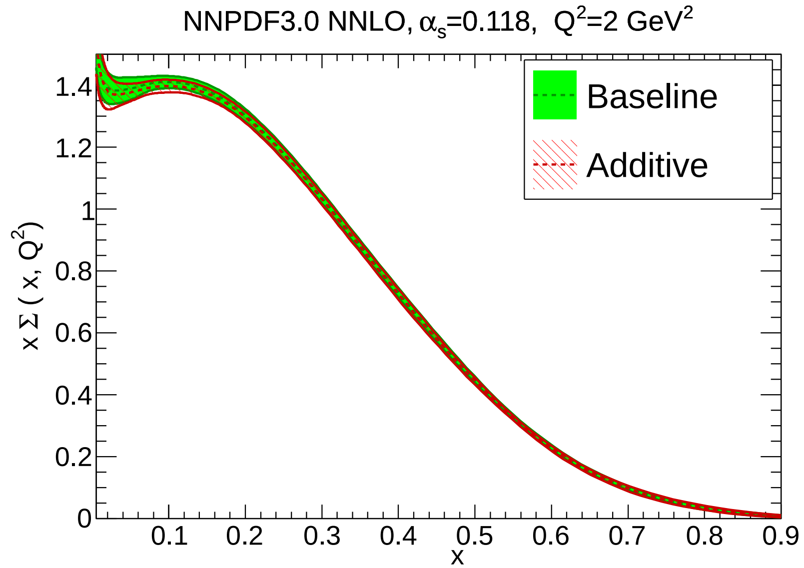
NLO, NNLO PDF UNC. & NLO TH. UNC.





MULTIPLICATIVE VS. ADDITIVE UNCERTAINTIES





- NORMALIZATION UNCERTAINTY PROPORTIONAL TO MEASURED VALUE ⇒ MULTIPLICATIVE
- WHAT ABOUT OTHER UNCERTAINTIES?
  IN COLLIDER MOSTLY MULTIPLICATIVE (A. Glazov)
- IN NNPDF3.0 DEFAULT ALL UNCERTAINTIES MULTPLICATIVE FOR HERA, TEVATRON, LHC
- REPEAT FIT WITH ALL UNCERTAINTIES ADDITIVE (AS IN NNPDF2.3)
- t_0 METHOD USED FOR MULTIPLICATIVE UNCERTAINTIES
- NEGLIGIBLE CHANGE SEEN

REQUIREMENTS FOR INCLUSION

PDFs TO BE INCLUDED IN THE COMBINATION MUST SATISFY REQUIREMENTS WHICH MAKE THEM COMPATIBLE
DOCUMENT IN PDF4LHC APRIL 2015 INDICO
SOME LISTED HERE (SEE DOCUMENT FOR FULL LIST):

- PROVIDE RESULTS AT NLO AND NNLO, WITH NNLO α_s, EVOLUTION BENCHMARKED AGAINST HOPPET OR QCDNUM
- SEPARATE TREATMENT OF α_s AS DISCUSSED
- USE A GENERAL-MASS VARIABLE FLAVOR NUMBER SCHEME WITH UP TO 5 FLAVORS
- CURRENT TECHNOLOGY: FITS MUST BE BASED ON APPROXIMATELY COMMON, GLOBAL SET OF DATA
  REQUEST TO RELAX THIS (HERAPDF)