PARTON DISTRIBUTIONS
FOR LHC RUN II

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI
DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

DESY THEORY WORKSHOP

HAMBURG, OCTOBER 2, 2015

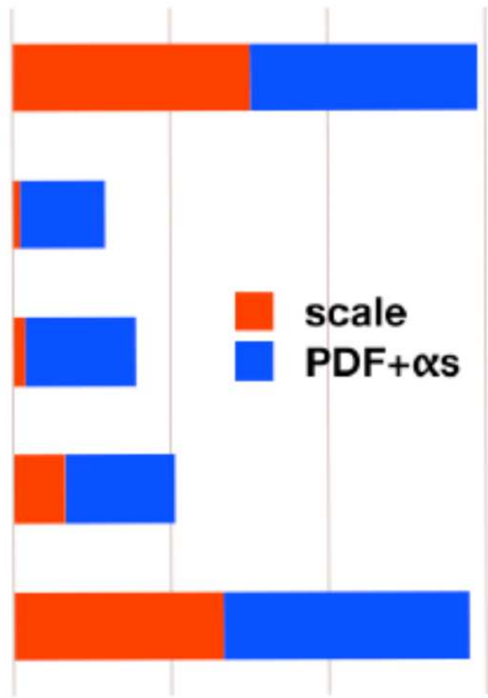
PROLOGUE

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%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
NNLO QCD +NLO EW	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 in TIME

	2008		2009		2010		2011	2012		2013		2014		2015
SET MONTH	CT6.6 (02)	NN1.0 (08)	MSTW (01)	ABKM09 (08)	NN2.0 (02)	CT10(N) (07)	NN2.1(NN) (07)	ABM11 (02)	NN2.3 (07)	CT10(NN) (02)	ABM12 (10)	NN3.0 (10)	MMHT (12)	CT14 (06)
F. T. DIS	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
ZEUS+H1-HI	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
COMB. HI	✗	✗	✗	✗	✔	✗	✔	✗	✔	✗	✔	✔	✗	✗
ZEUS+H1-HII	✗	✗	✗	✗	✗	✗	some	✗	✗	some	✗	✔	✗	✗
HERA JETS	✗	✗	✔	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗
F. T. DY	✔	✗	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
TEV. W+Z	✔	✗	✔	✗	✔	✔	✔	✗	✔	✔		✔	✔	✔
TEV. JETS	✔	✗	✔	✗	✔	✔	✗	✔	✔	✔	✗	✔	✔	✔
LHC W+Z	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	some	✔	✔	✔
LHC JETS	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗	✔	✔	✔
TOP	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✔	✗	✗
W+C	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗
W p_T	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗	✗

- INCREASINGLY WIDE DATASET USED FOR PDF DETERMINATION: DATA-DRIVEN ACCURACY (?)
- HERAPDF: OPPOSITE CHOICE (ONLY HERA DATA): FIT INCLUDING FULL COMBINED HERA DIS DATASET (HERAPDF2.0)
- THEORETICAL AND METHODOLOGICAL IMPROVEMENTS/CHOICES:
  - MSTW, ABKM: ALL NNLO; NNPDF NNLO SINCE 07/11 (2.1), CT SINCE 02/13 (CT10)
  - MSTW, CT ALL GM-VFN HEAVY QUARKS (TR, ACOT); NNPDF GM-VFN (FONLL) SINCE 01/11 (2.1); ABM: FFN

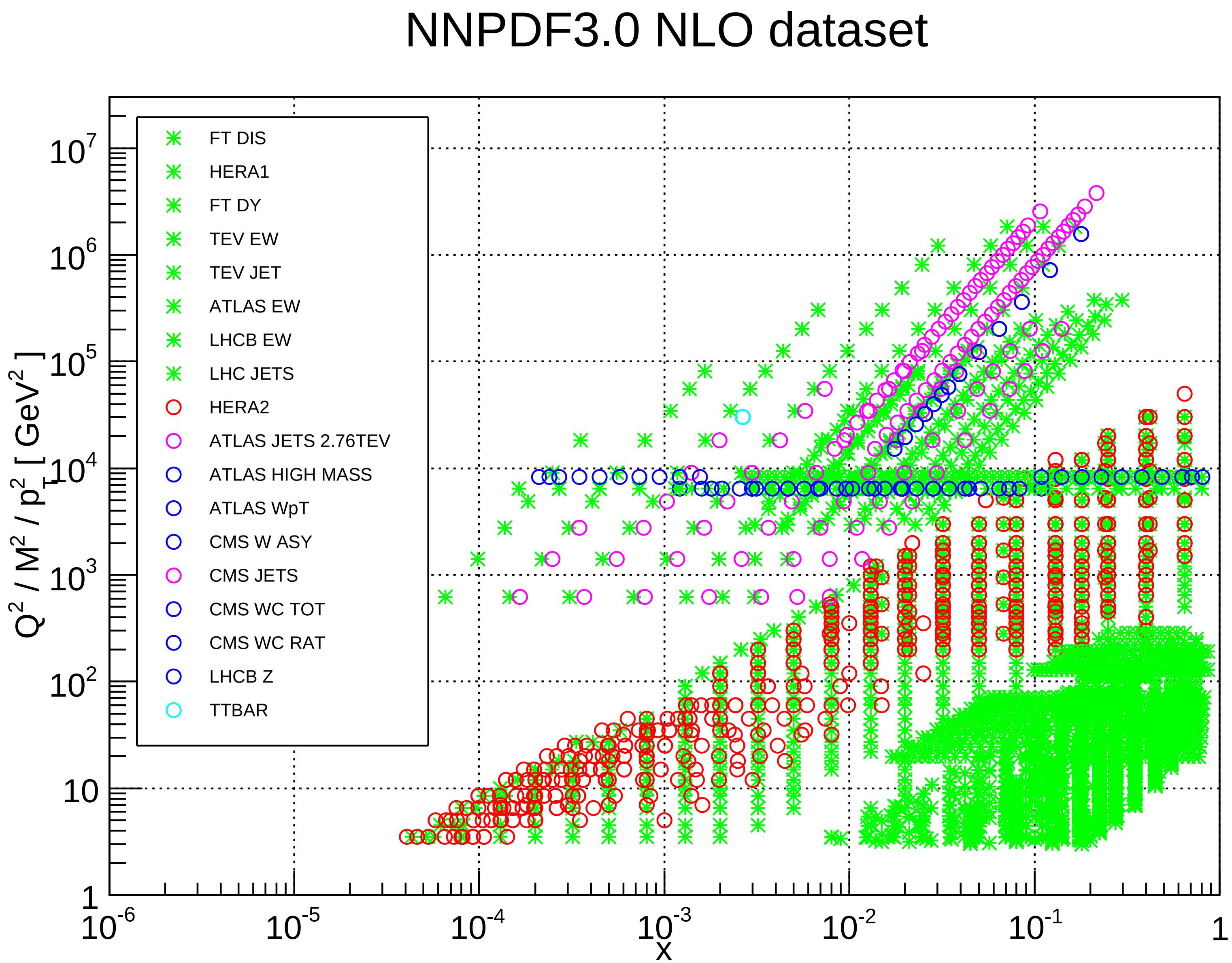
SUMMARY

- WHERE ARE WE (AND HOW DID WE GET THERE): PDFs AND DATA
- THE PDF4LHC PRESCRIPTION FOR LHC RUN II
- THEORETICAL UNCERTAINTIES AND ISSUES
- BEYOND LHC II

GLOBAL FITS: THE DATASET IN DETAIL

	NNPDF3.0	MMHT14	CT14
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	✗	✔	✔
D0 Run-II W asym	✗	✗	✔
ATLAS high-mass DY	✔	✔	✔
CMS 2D DY	✔	✔	✗
ATLAS W,Z rap	✔	✔	✔
ATLAS W p_T	✔	✗	✗
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

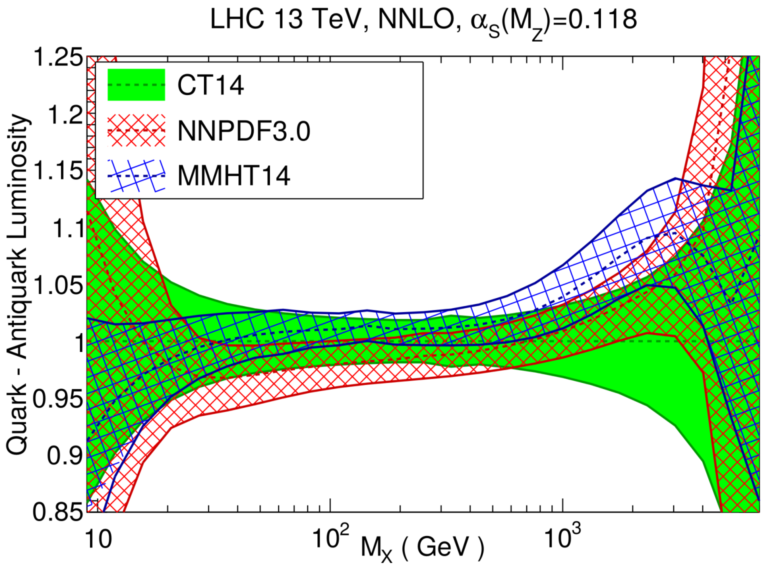
THE NNPDF3.0 DATASET



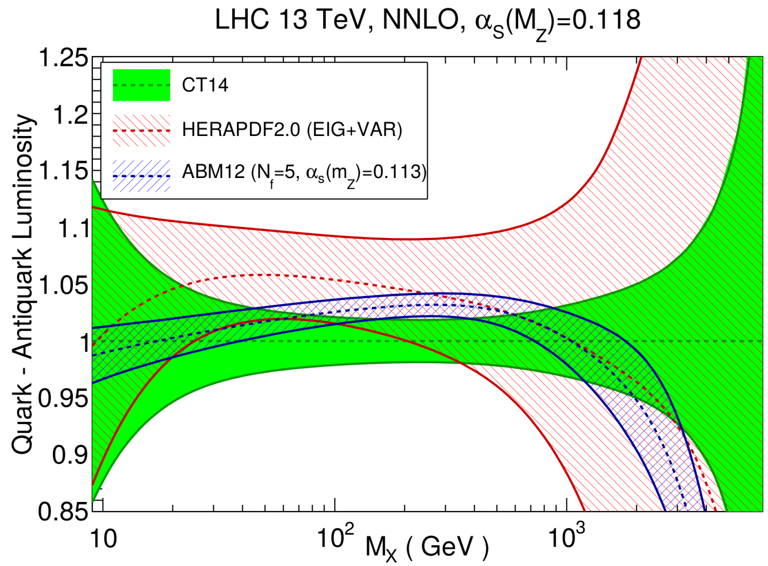
PARTON LUMINOSITIES

QUARK-ANTIQUARK

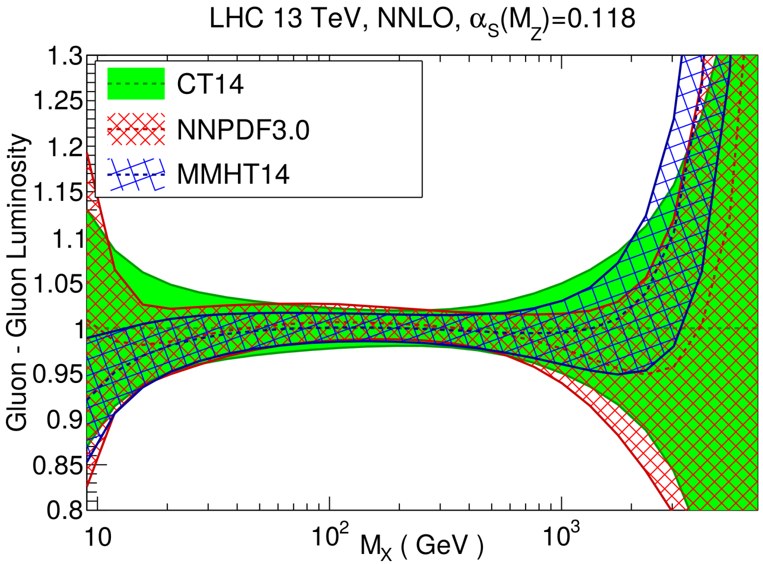
GLOBAL

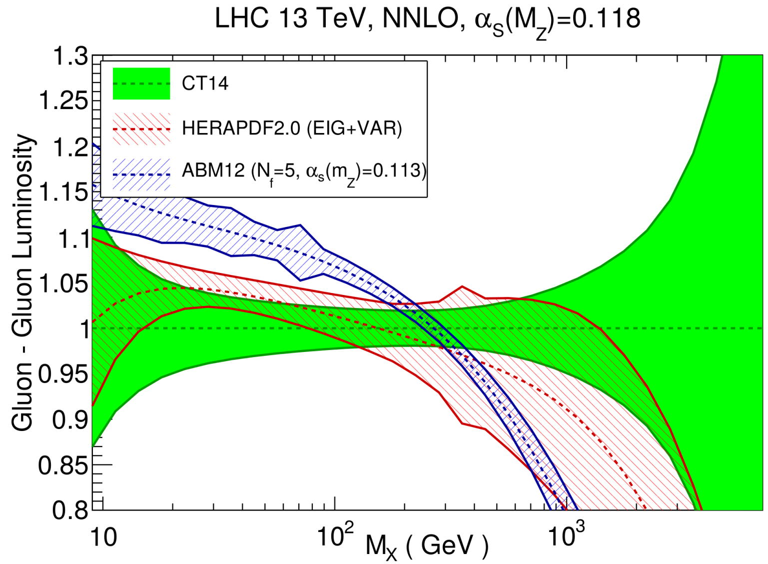


REDUCED



GLUON-GLUON





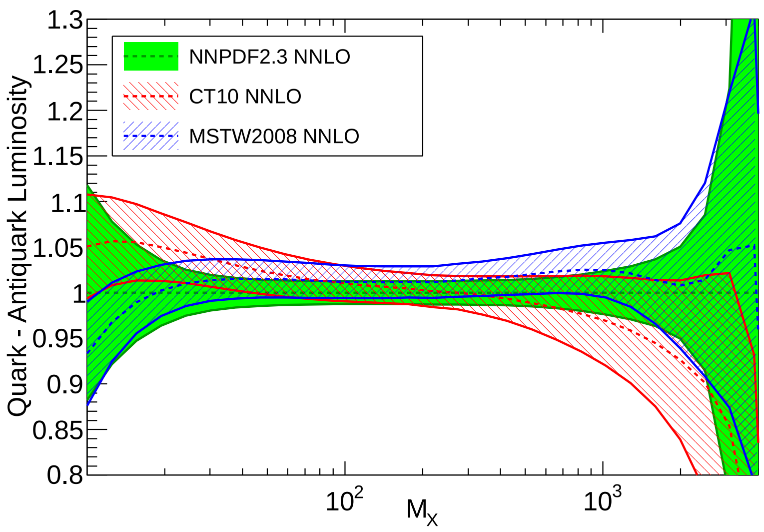
- GLOBAL FITS AGREE WELL
- FITS BASED ON REDUCED DATASET HAVE EITHER LARGE UNCERTAINTIES, OR SHOW SIZABLE DEVIATIONS

PARTON LUMINOSITIES

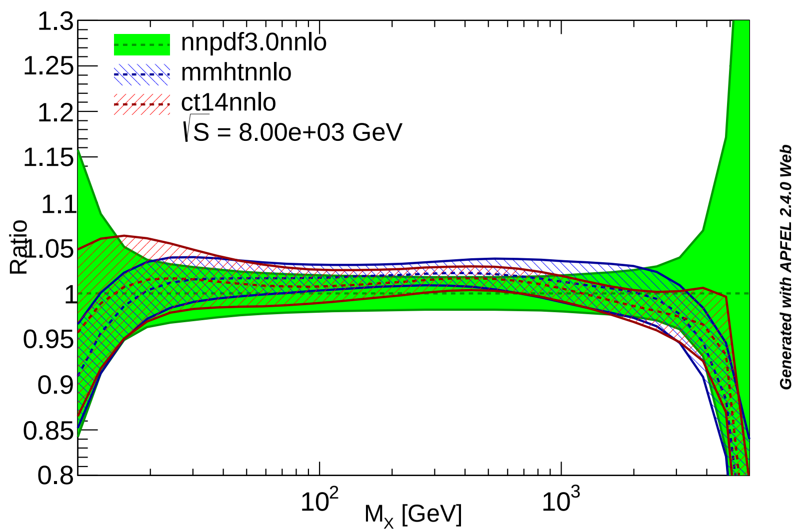
RECENT PROGRESS

QUARK-QUARK

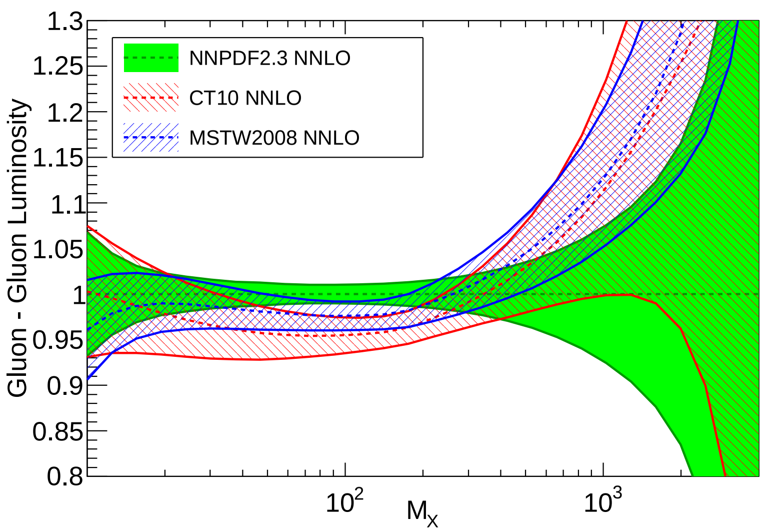
2012

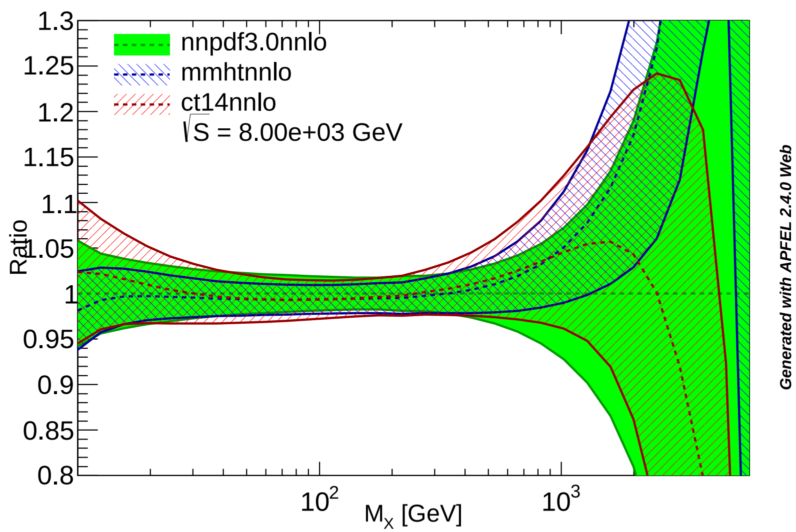


2015



GLUON-GLUON





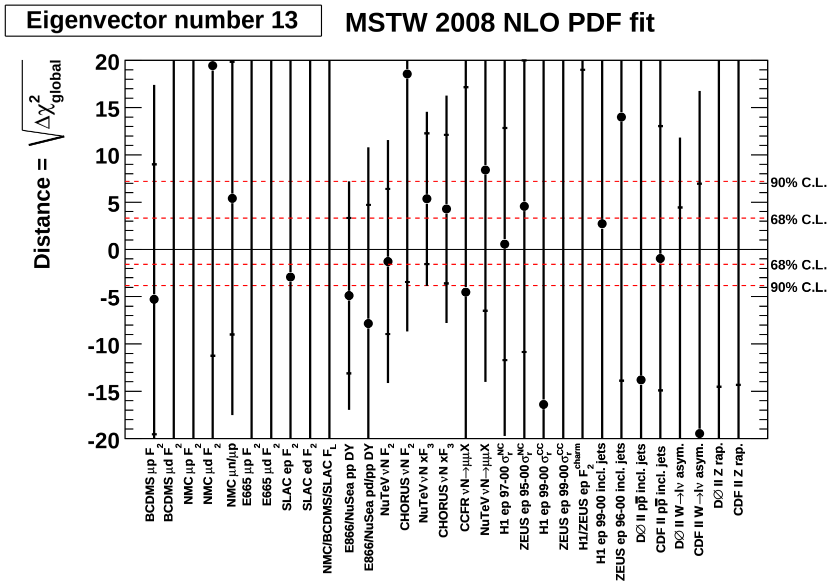
PDF UNCERTAINTIES

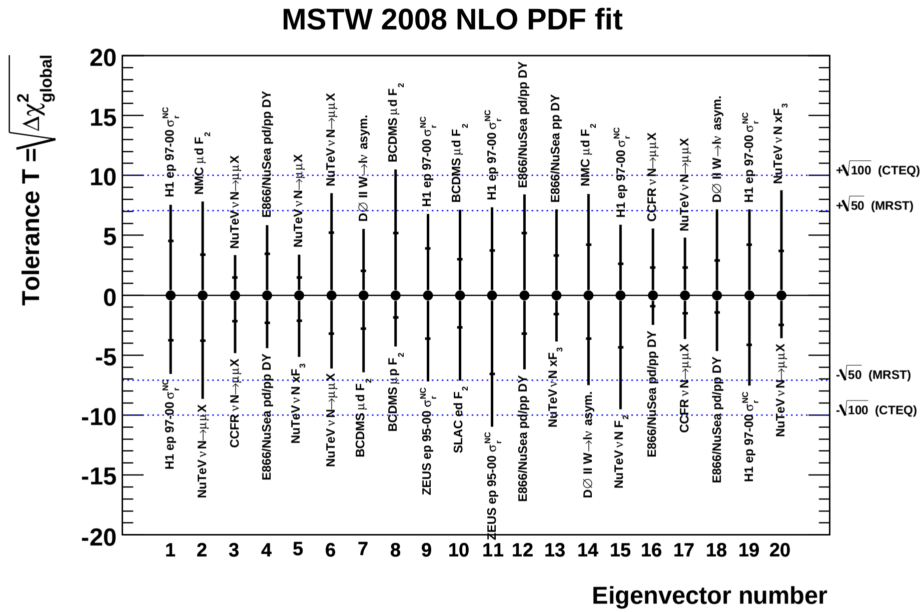
- Q: WHY ARE PDF UNCERTAINTIES ON GLOBAL FITS OF SIMLAR SIZE?
  - SIMILAR DATASETS
  - BUT DIFFERENT PROCEDURES
- A: UNCERTAINTY TUNING

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

PDF UNCERTAINTIES

- Q: WHY ARE PDF UNCERTAINTIES ON GLOBAL FITS OF SIMLAR SIZE?
  - SIMILAR DATASETS
  - BUT DIFFERENT PROCEDURES
- A: UNCERTAINTY TUNING

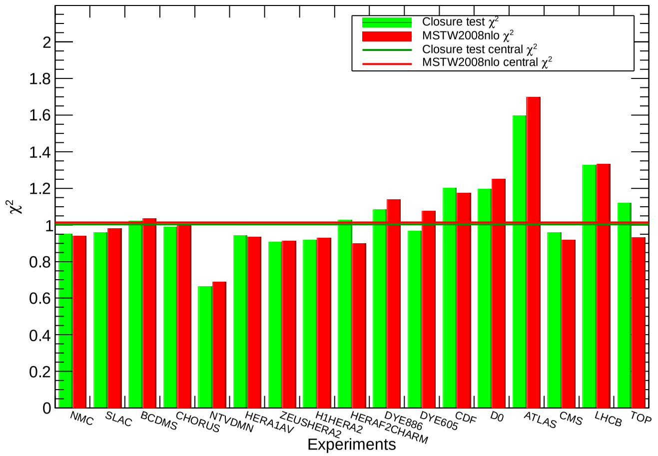
CLOSURE TESTS (NNPDF)

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

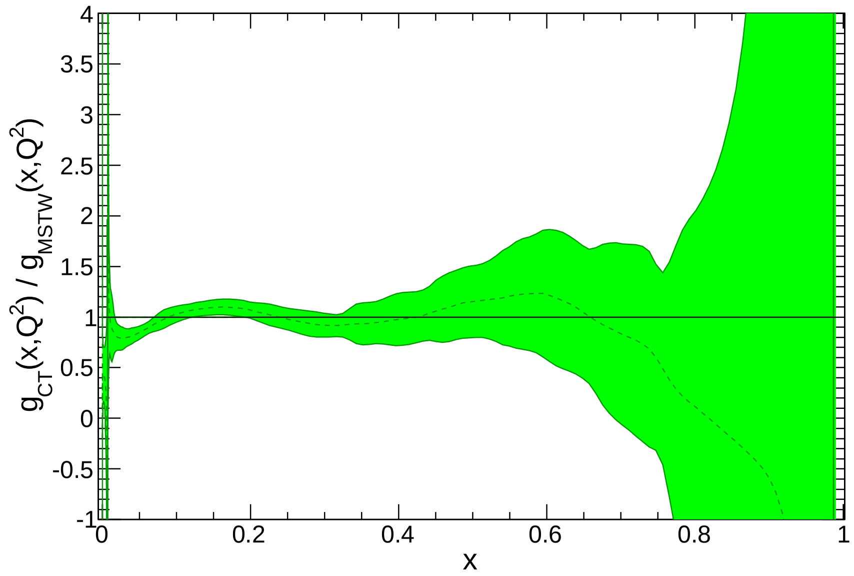
Distribution of χ^2 for experiments



- 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.

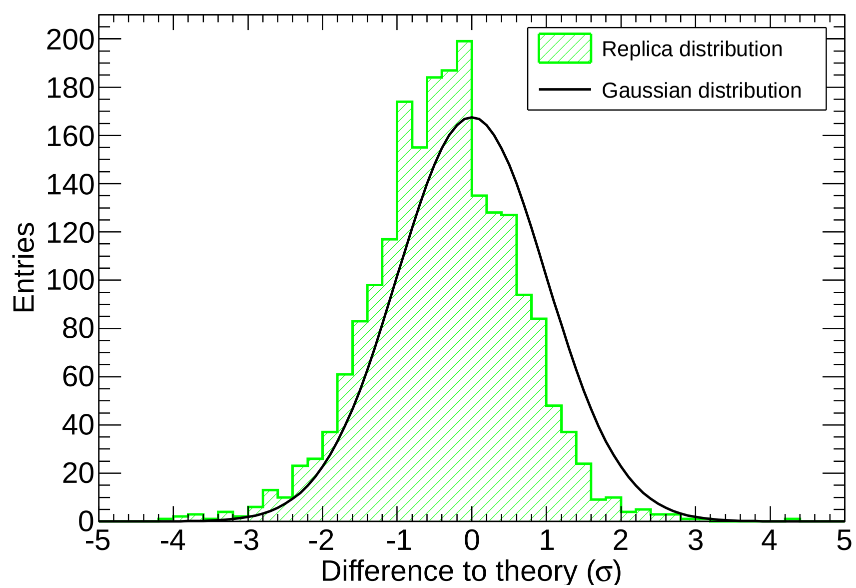
THE GLUON: FITTED/"TRUE"

Ratio of Closure Test g to MSTW2008



NORM. DISTRIBUTION OF DEVIATIONS

Distribution of single replica fits in level 2 uncertainties



PROGRESS

- Q: WHAT HAS DRIVEN DRIVES THE IMPROVED AGREEMENT OF GLOBAL FITS
  - SIMILAR DATASETS
  - BUT DIFFERENT PROCEDURES
- A: DATA+METHODOLOGY

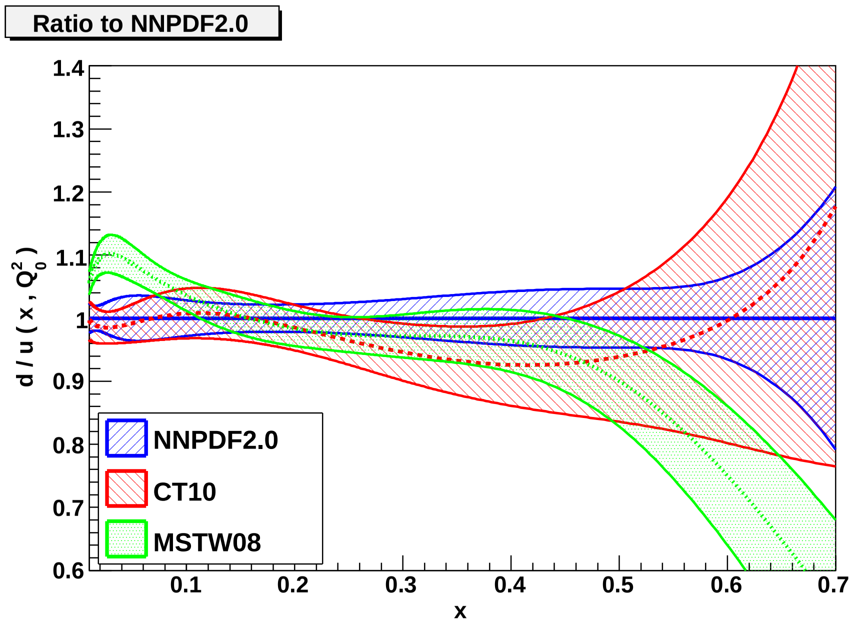
METHODOLOGY

	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

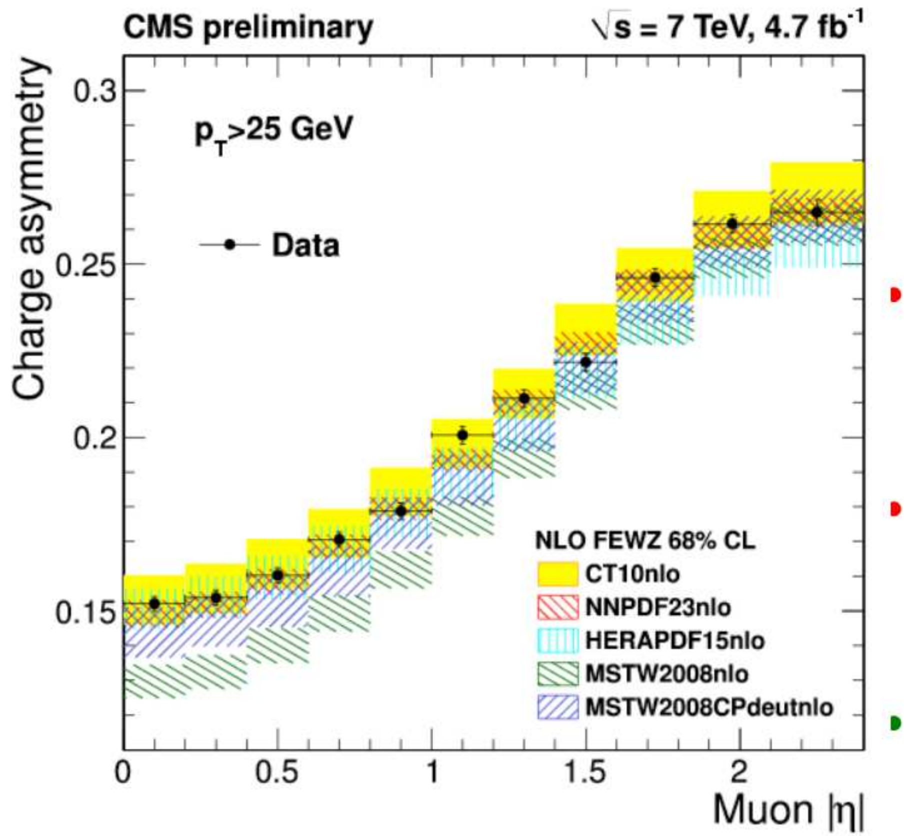
- MMHT, CT10 larger # of parms., orthogonal polynomials
- NNPDF closure test

DATA ⇒ METHODOLOGY
MSTW/MMHT: THE d/u RATIO

THE d/u RATIO



THE CMS W ASYMMETRY

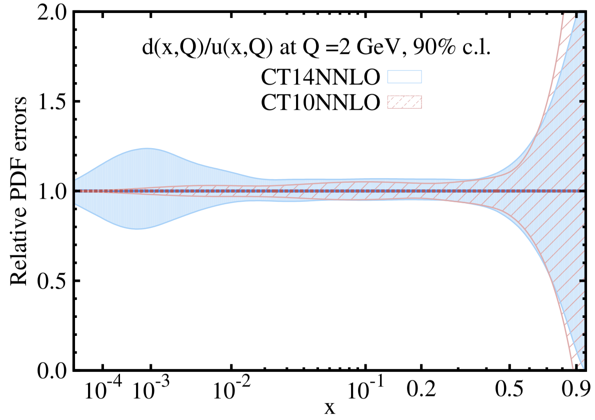


- LONG-STANDING DISCREPANCY IN THE d/u RATIO BETWEEN MSTW AND OTHER GLOBAL FITS
- RESOLVED BY W ASYMMETRY DATA
- EXPLAINED BY INSUFFICIENTLY FLEXIBLE PDF PARAMETRIZATION ⇒ FIXED IN MSTW08DEUT/MMHT

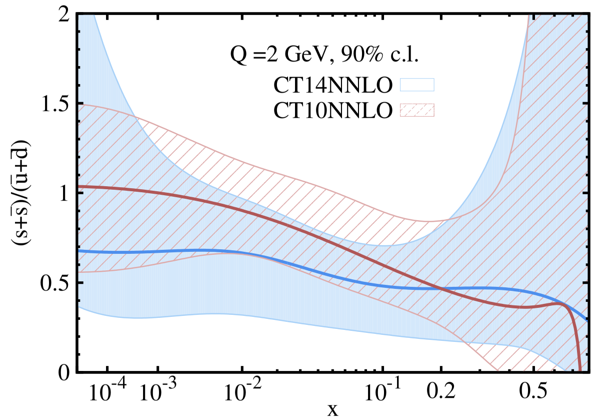
DATA ⇒ METHODOLOGY

CT14: EXTENDED PARAMETRIZATION

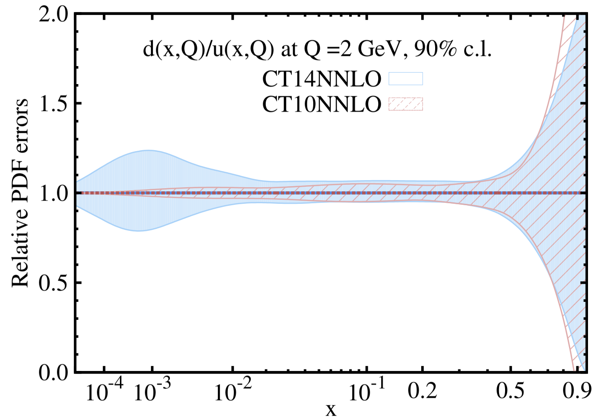
d/u RATIO



$\bar{d}/\bar{u}$ RATIO



$(s+\bar{s})/(\bar{u}+\bar{d})$ RATIO



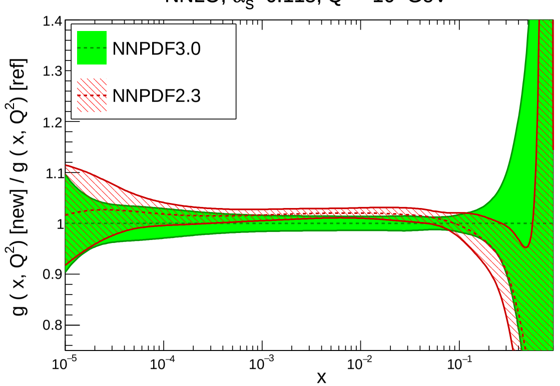
- D0 RUN II CHARGE-ASYMMETRY (NOT INCLUDED BY OTHERS) DATA AFFECT u/d
- LHC W/Z DATA IMPACT STRANGENESS
- SOMEWHAT INCREASED UNCERTAINTIES DUE TO MORE FLEXIBLE FUNCTIONAL FORM

DATA ⇒ METHODOLOGY
NNPDF: 3.0 VS. 2.3

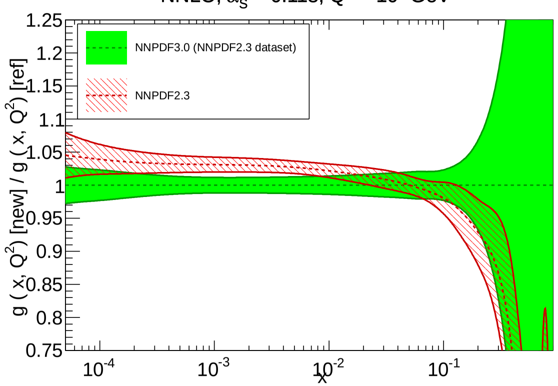
- REPEAT THE 3.0 FIT BUT WITH 2.3 DATASET
- COMPARE WITH 2.3 DATA & METHODOLOGY; 2.3 DATA BUT 3.0 METHODOLOGY; 3.0 DATA & METHODOLOGY

THE GLUON DISTRIBUTION

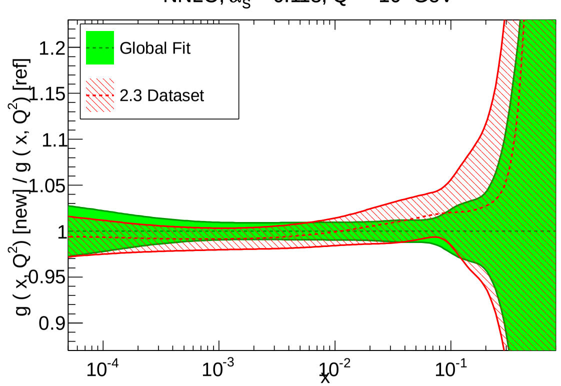
DEFAULT 3.0 VS DEFAULT 2.3



DEFAULT 2.3 VS. 2.3 DATA



DEFAULT 3.0 VS 2.3 DATA

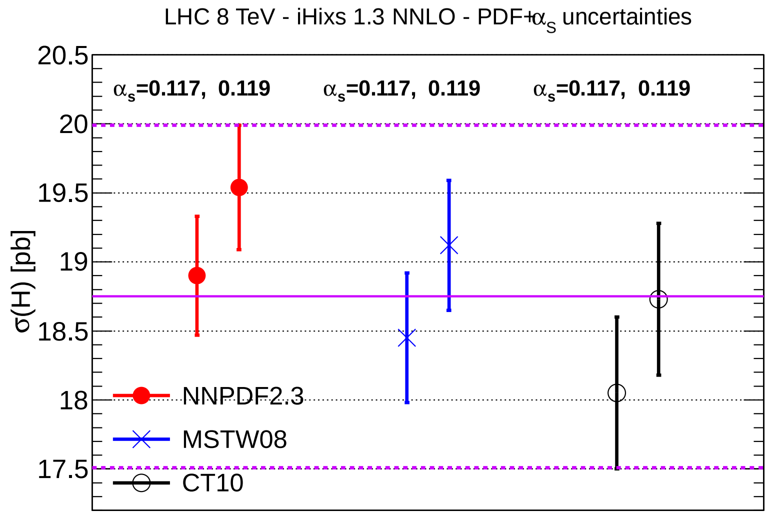


- THE METHODOLOGY HAS A DOMINANT EFFECT ON THE GLUON
- EFFECT OF DATA SUBDOMINANT,
  LARGER ON OTHER COMBINATIONS (VALENCE)

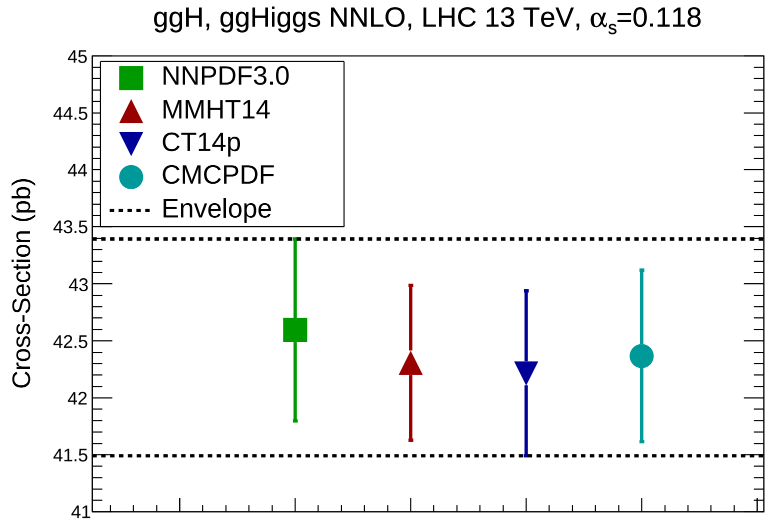
PDFs for LHC Run II

RECENT PROGRESS:
HIGGS IN GLUON FUSION

2012



2015



- PDF4LHC PRESCRIPTION 2012: ENVELOPE, PDF UNCERTAINTY $\sim 6\%$
- PDF4LHC PRESCRIPTION 2015: STATISTICAL COMBINATION, PDF UNCERTAINTY $\sim 2\%$

THE 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 VS. HESSIAN DELIVERY

- MONTE CARLO: A SET OF PDF REPLICAS IS DELIVERED;
QUANTITIES COMPUTED FOR EACH REPLICA: CENTRAL VALUE IS THE MEAN, UNCERTAINTY IS STANDARD DEVIATION
- HESSIAN: A CENTRAL SET AND ERROR SETS ARE DELIVERED;
CENTRAL SET PROVIDES CENTRAL PREDICTION, UNCERTAINTY IS THE SUM IN QUADRATURE OF ERROR DEVIATIONS

TREATMENT OF α_s

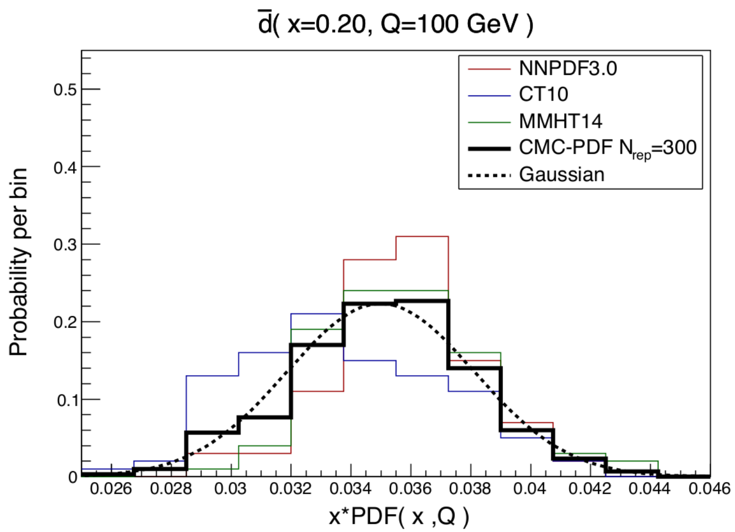
- PDFS ARE DELIVERED FOR EACH VALUE OF α_s
- PDF AND α_s UNCERTAINTIES TO BE KEPT SEPARATE
(SEE BELOW FOR α_s UNCERTAINTY)

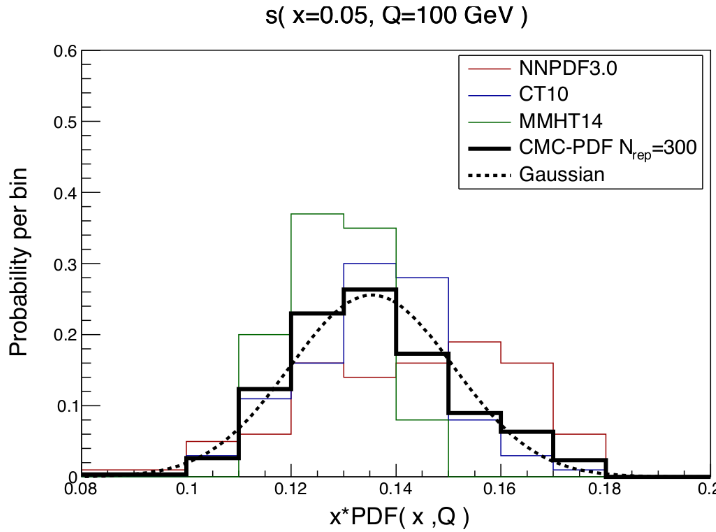
MONTE CARLO COMBINATION

(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



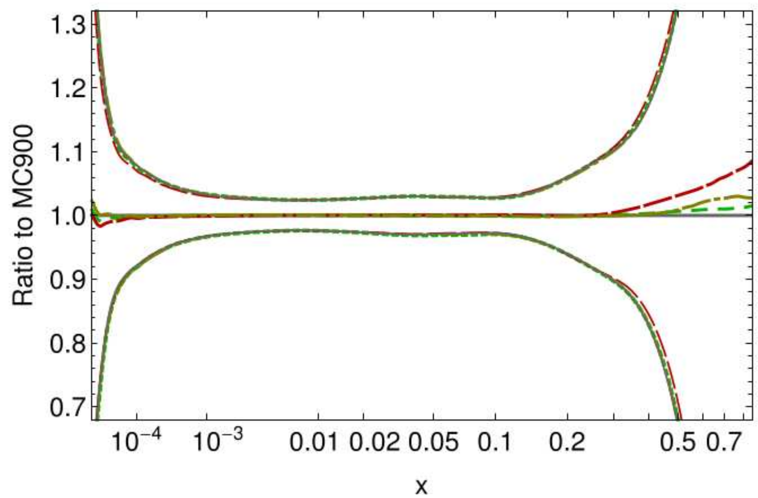


CURRENT COMBINED SET

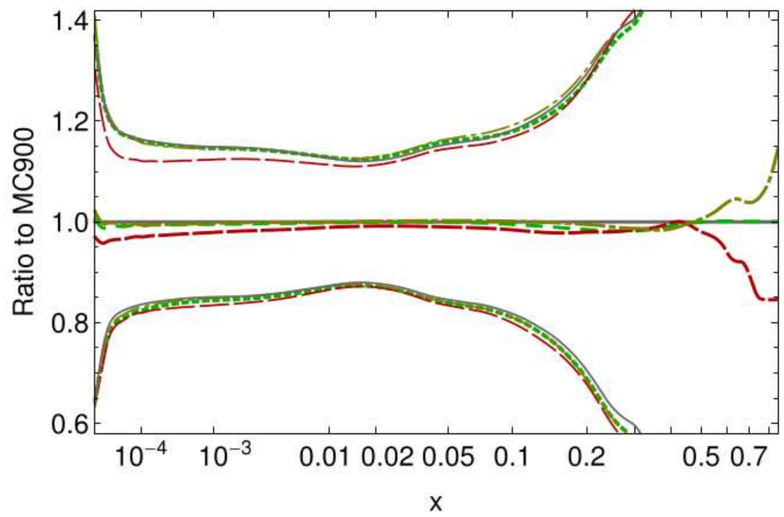
- INCLUDES CT14, MMHT, NNPDF3.0
- 900 REPLICAS (300 FOR EACH SET) ENSURE PRECENTAGE ACCURACY ON ALL QUANTITIES

300, 900, 1800 REPLICAS
(RATIO TO 900)

gluon



strange

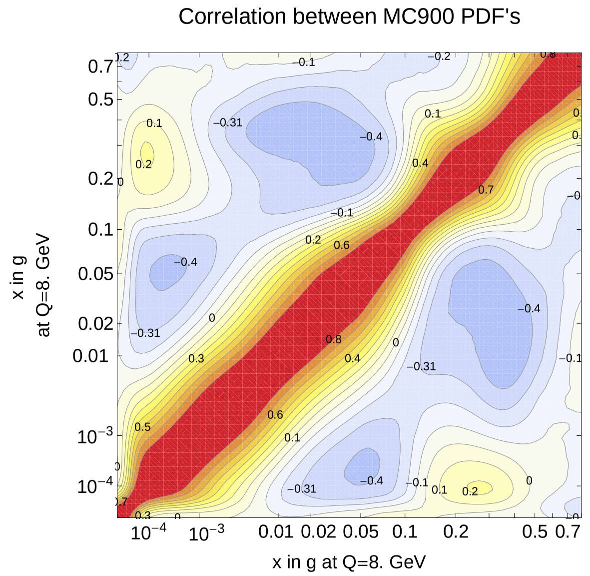


TOOLS FOR DELIVERY

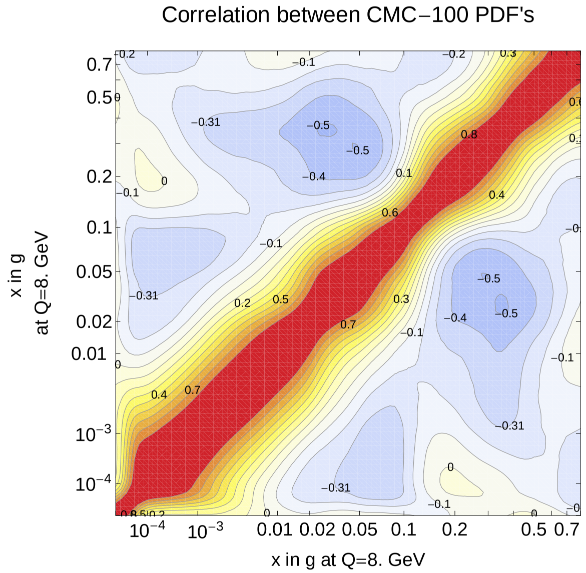
- COMBINED MC SET IS LARGE (900 REPLICAS)
- HESSIAN DELIVERY OFTEN DESIRABLE (PDF UNCERTAINTIES AS NUISANCE PARAMETERS)
- CMC (1504.06469): GA COMPRESSION OF MC SET TO A SMALLER SET WITH MINIMAL INFORMATION LOSS (900 $\to$ 40-100 REPLICAS)
- META-PDFS (1401.0013) OR MC-H (1505.06736) PDFS: HESSIAN REPRESENTATION 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

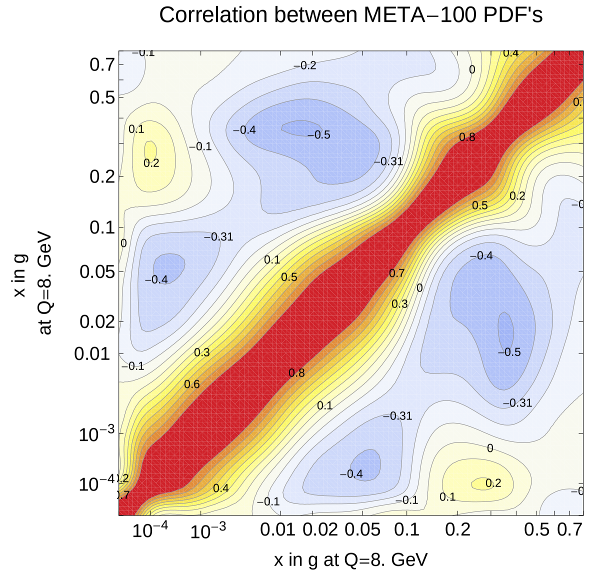
STARTING COMBINED SET



COMPRESSED MC SET



META-PDF SET



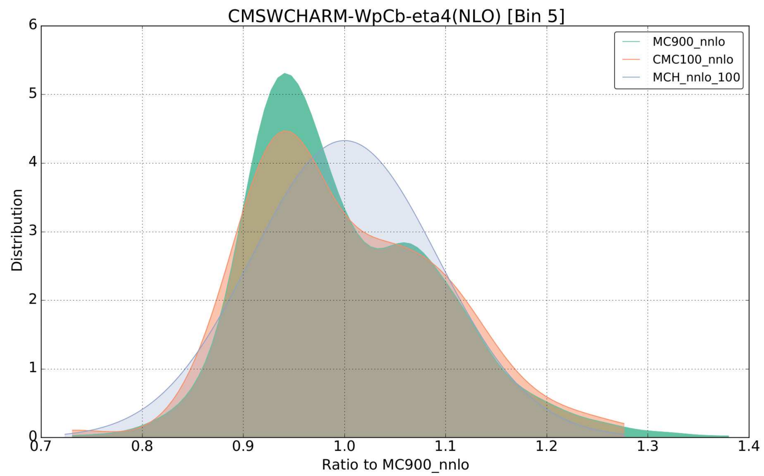
MONTECARLO PDFS: NONGAUSSIAN BEHAVIOUR

DEVIATION FROM GAUSSIANITY OBSERVED

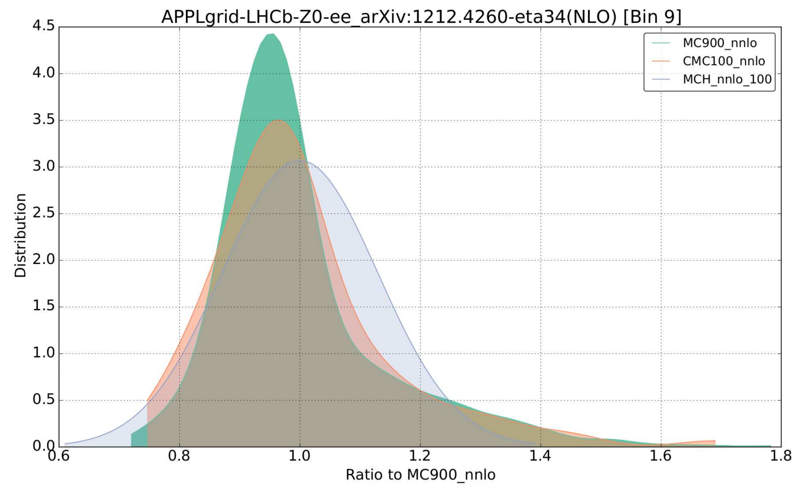
E.G. AT LARGE x, DUE TO LARGE UNCERTAINTY & POSITIVITY BOUNDS (MAY BE RELEVANT FOR SEARCHES)

MONTE CARLO COMPARED TO HESSIAN

CMS $W + c$ production



LHCb electrons



(Carrazza, Latorre, Rojo, Watt, 2015)

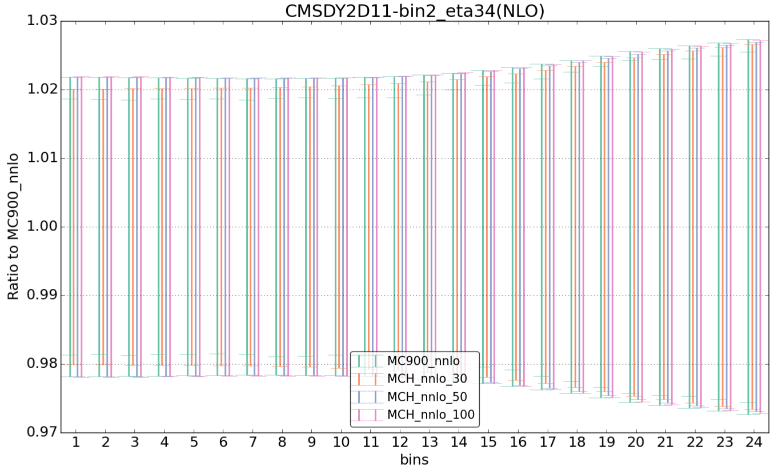
- MONTE CARLO PDFS REPRODUCE NONGAUSSIAN, HESSIAN FAIL
- COMPRESSION EFFECTIVELY REPRODUCES NONGAUSSIAN SHAPES
- PROBLEM DOES NOT ARISE FOR BULK OF DATA $\Rightarrow$ HESSIAN ADEQUATE!

HESSIAN PDFs: HIGH ACCURACY

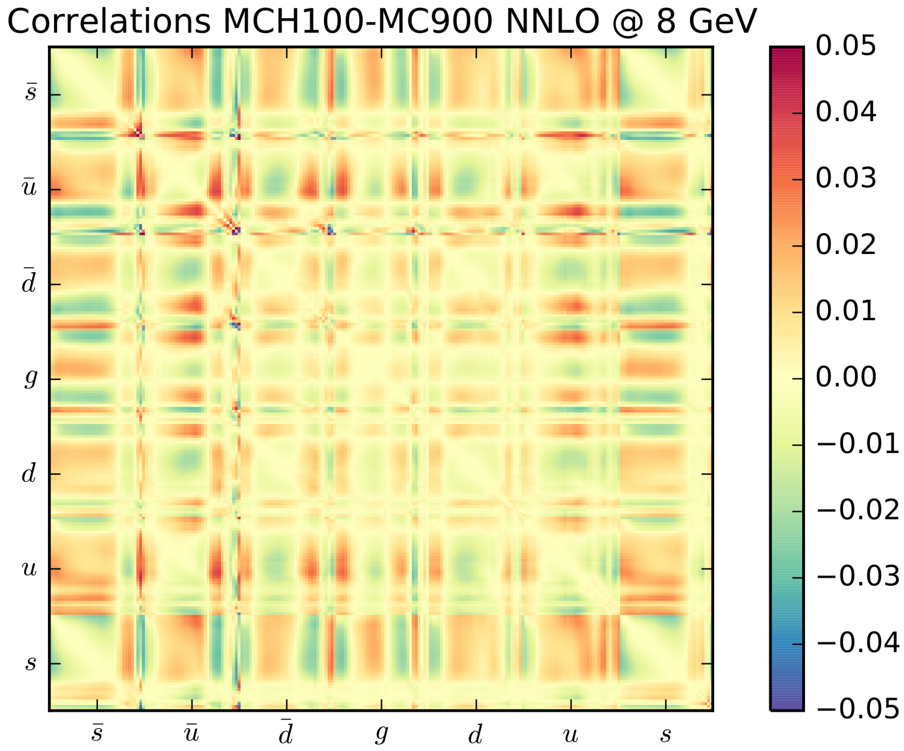
- FOR STANDARD CANDLES OR HIGGS PRODUCTION, GAUSSIAN APPROXIMATION ACCURATE
- HESSIAN REPRESENTATION EXTREMELY ACCURATE WITH 100 ERROR SETS

HESSIAN: FROM 30 TO 100 SETS VS MC PRIOR

CMS double diff DY



PDF correlations
(deviation from exact)



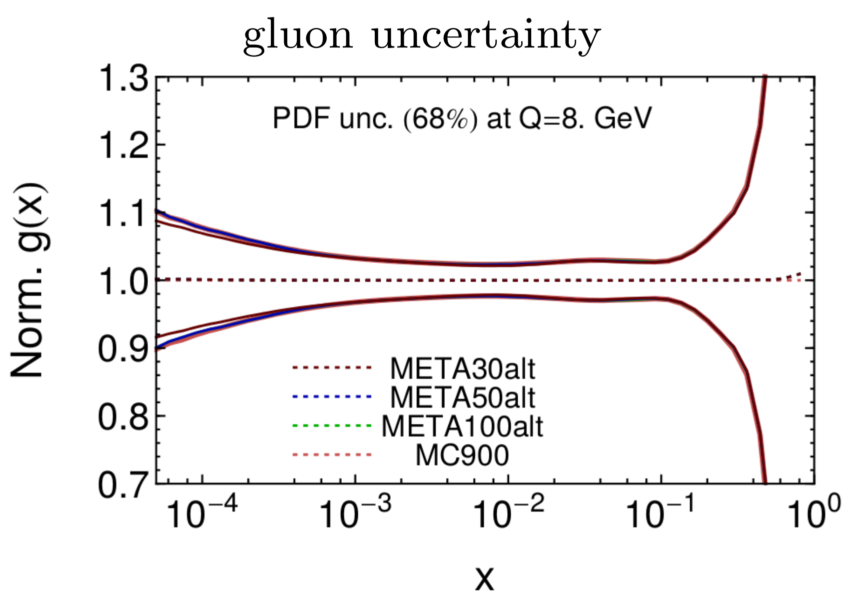
(Carrazza, Kassabov, S.F., Latorre, Rojo, 2015)

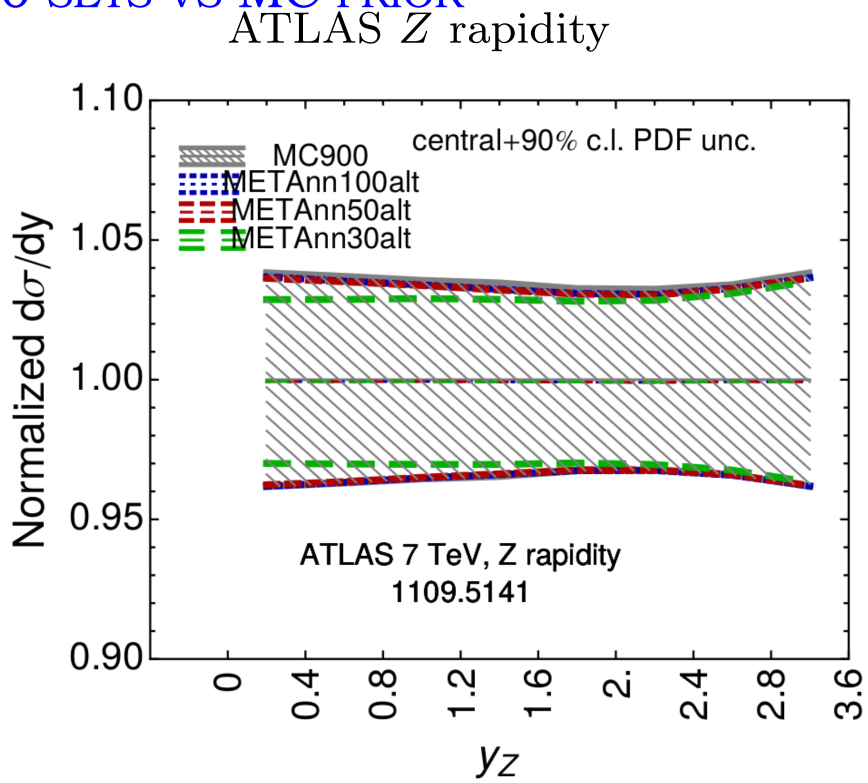
- UNCERTAINTIES PERFECTLY REPRODUCED
- CORRELATION MATRIX OF PDFs TO PERCENT ACCURACY

HESSIAN PDFs: FAST IMPLEMENTATION

- FOR ACCEPTANCE CALCULATIONS OR EXTRAPOLATION FROM FIDUCIAL TO FULL, SOME LOSS OF ACCURACY IS TOLERABLE
- SMALL NUMBER OF NUISANCE PARAMETERS OFTEN DESIRABLE
- HESSIAN REPRESENTATION WITH 30 ERROR SETS ADEQUATE (ESPECIALLY IN DATA REGION)

HESSIAN: FROM 100 TO 30 SETS VS MC PRIOR





(Nadolsky, Gao, 2014)

- PDFs REASONABLY WELL REPRODUCED IN DATA REGION
- UNCERTAINTIES ON OBSERVABLES REPRODUCED TO BETTER THAN 10%, USUALLY MUCH BETTER

THEORETICAL ISSUES

THEORETICAL UNCERTAINTIES ON PDFs:

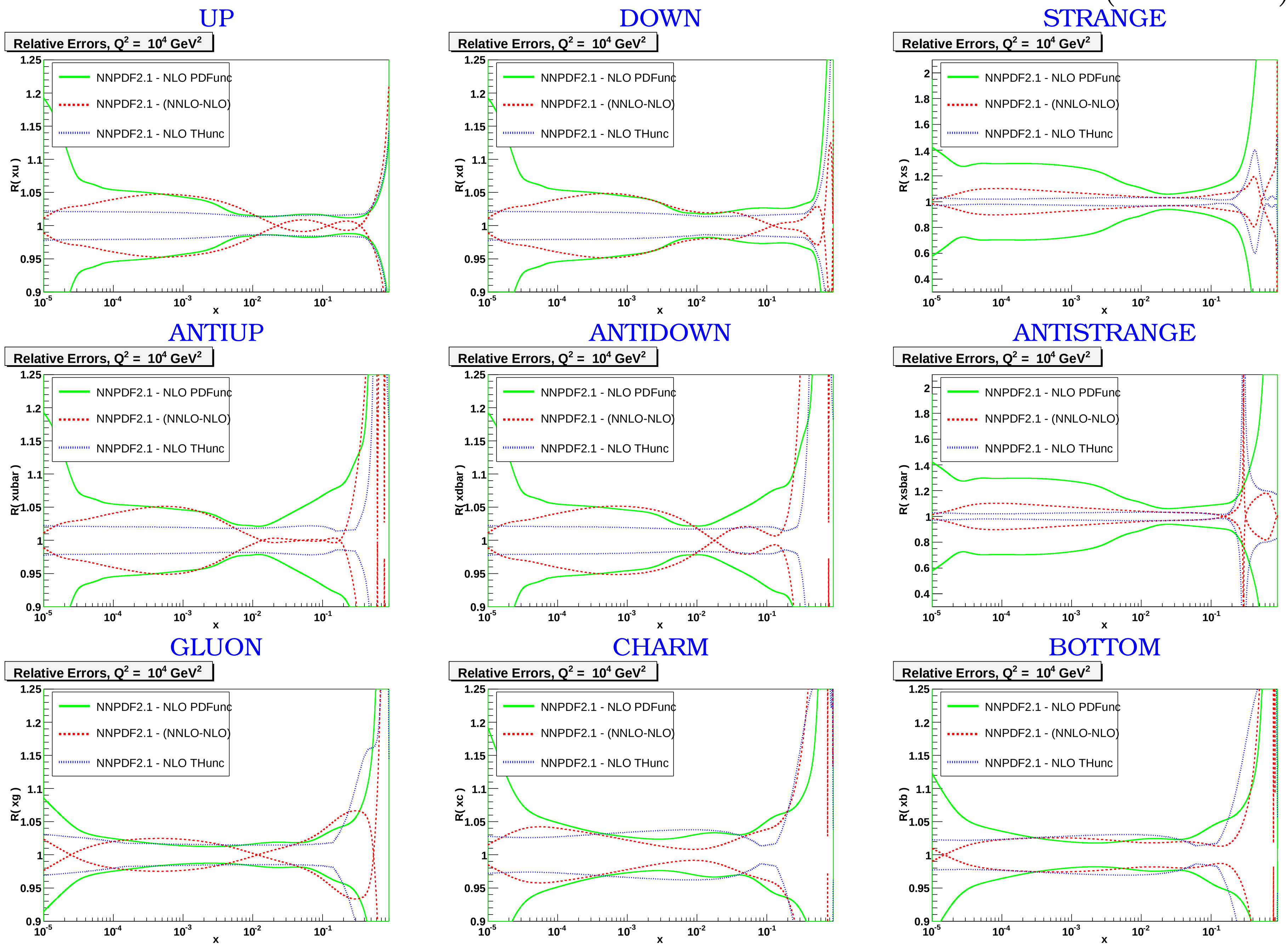
- PDFs ARE DETERMINED BY COMPARING TO DATA THEORY AT SOME FINITE ORDER
- AFFECTED BY THEORETICAL UNCERTAINTY JUST LIKE HARD CROSS-SECTIONS
- NOT INCLUDED IN CURRENT "PDF UNCERTAINTY" (ACCOUNTS ONLY DATA & METHODOLOGY)

CAN WE ESTIMATE THEM?

- SCALE VARIATION DIFFICULT:
  CORRELATED BETWEEN PROCESSES? HOW DOES IT CORRELATE WITH PROCESSES IN WHICH PDFs ARE USED?
- AT NLO: WE KNOW THE SHIFT TO NNLO
- AT NNLO: LOOK AT THE BEHAVIOUR OF THE PERTURBATIVE EXPANSION (CACCIARI-HOUDEAU)

THEORETICAL UNCERTAINTIES

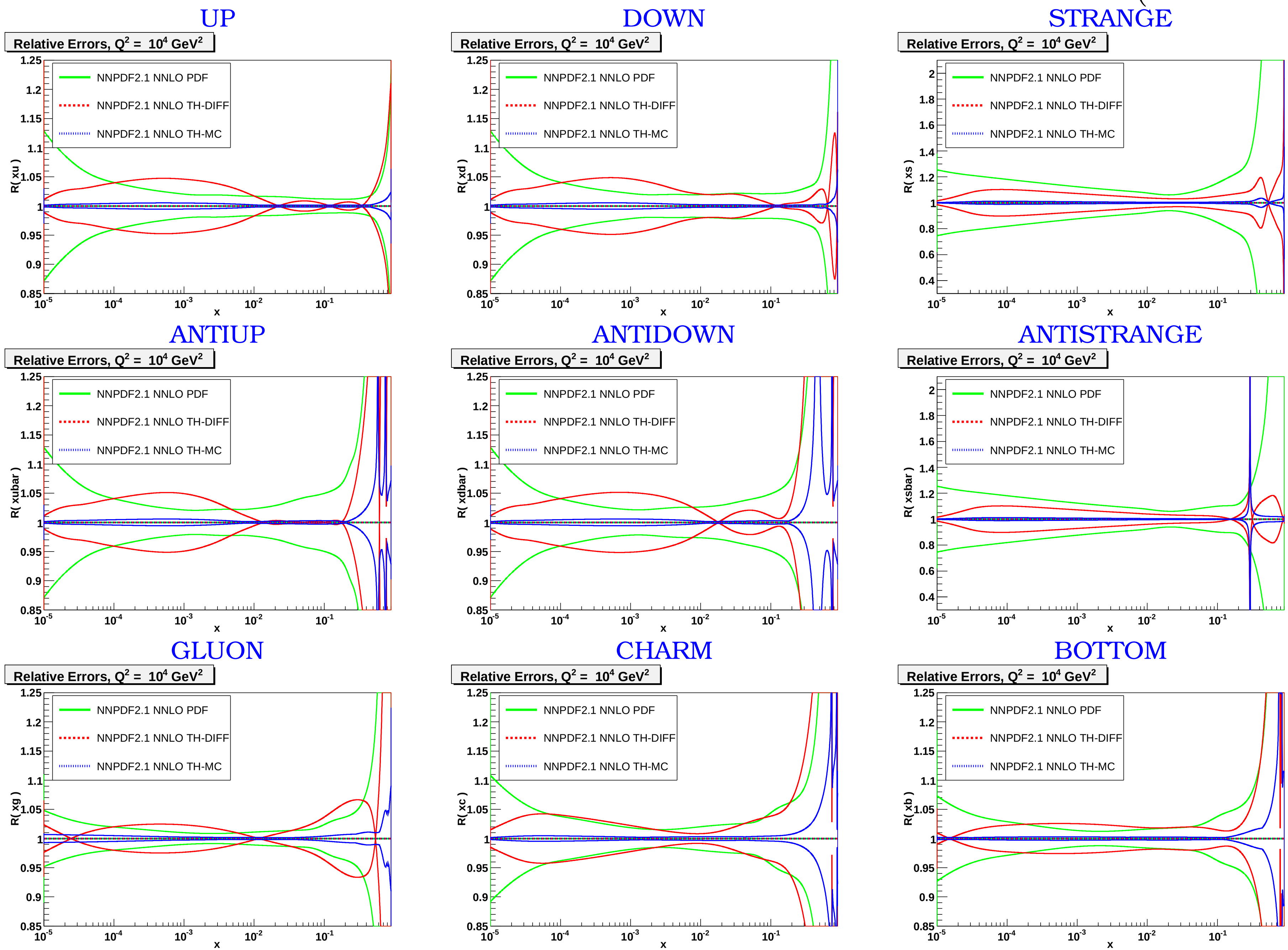
NLO PDF UNC. VS NLO-NNLO SHIFT VS NLO CACCIARI-HOUDEAU (NNPDF2.1)



THEORETICAL UNCERTAINTY ON NLO PDF IS ORDER 5% $\Rightarrow$ COMPARABLE TO PDF UNCERTAINTY

THEORETICAL UNCERTAINTIES

NNLO PDF UNC. VS NLO-NNLO SHIFT VS NNLO CACCIARI-HOUDEAU (NNPDF2.1)



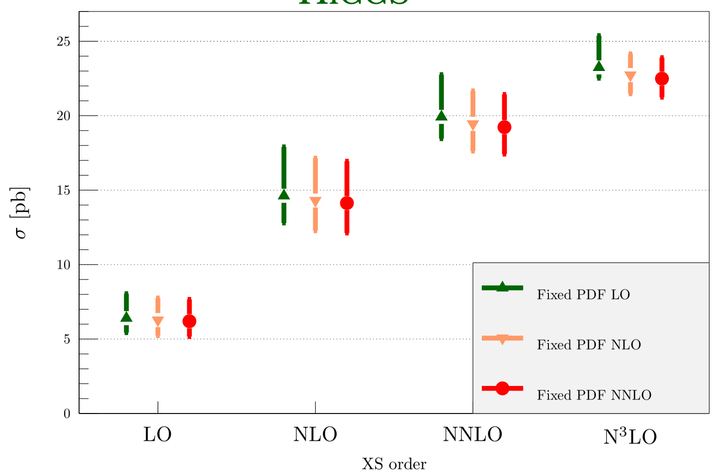
THEORETICAL UNCERTAINTY ON NNLO PDF IS ORDER 1% $\Rightarrow$ SMALLER THAN PDF UNCERTAINTY

N^{3}LO PDFs:

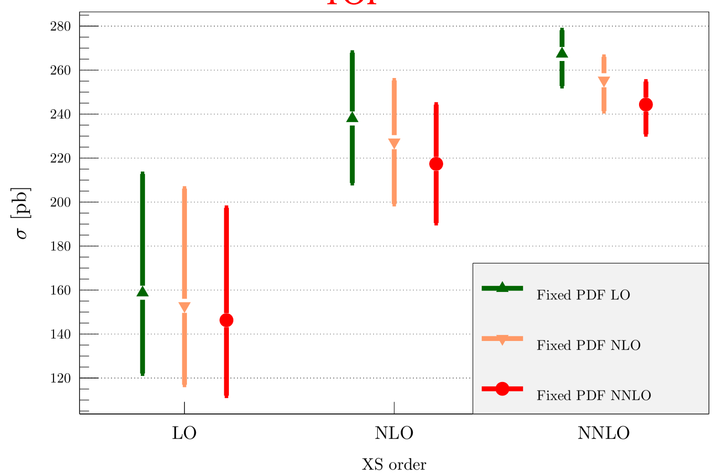
- NEEDED AT THE 1% ACCURACY LEVEL
- IMPACT OF N^3LO DEPENDS ON PROCESS:
  - HIGGS GLUON FUSION: PERTURBATIVE DEP. OF PDF NEGLIGIBLE IN COMPARISON TO MATRIX ELEMENT $\Rightarrow$ N^{3}LO NOT NEEDED
  - TOP: PERTURBATIVE DEP. OF PDF SMALLER, BUT NOT NEGLIGIBLE IN COMPARISON TO MATRIX ELEMENT, ANTICORRELATED TO IT $\Rightarrow$ N^{3}LO NECESSARY

SCALE UNCERTAINTY & DEP. ON PERTURBATIVE ORDER

HIGGS



TOP



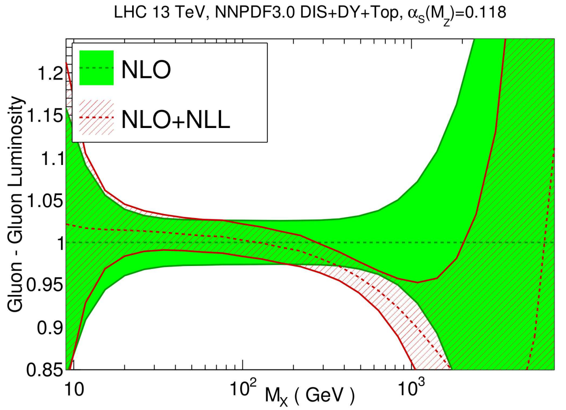
(s.f., Isgrò, Vita, 2014)

WHEN WILL WE HAVE THEM?

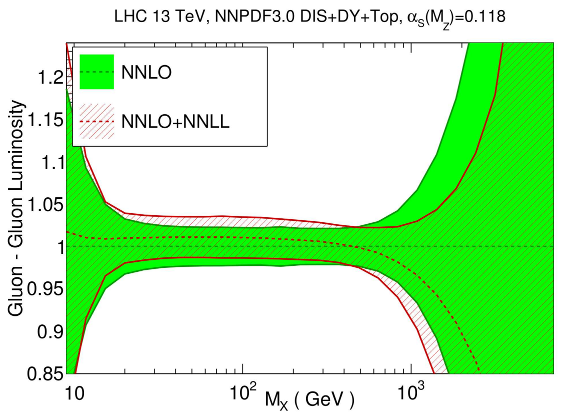
- N^{3}LO DIS COEFFICIENT FUNCTIONS KNOWN
- BOTTLENECK: N^3LO ANOMALOUS DIMENSIONS
- ANOMALOUS DIMENSIONS: LO: 1974; NLO: 1981; NNLO: 2004; N^{3}LO: 2030?

RESUMMED PDFs

GLUON: NLO VS NLL



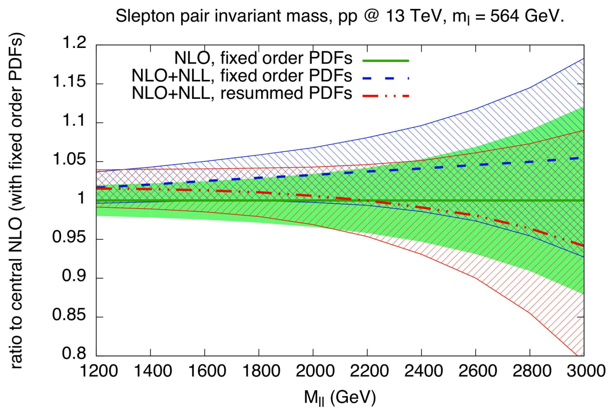
GLUON: NNLO VS NNLL



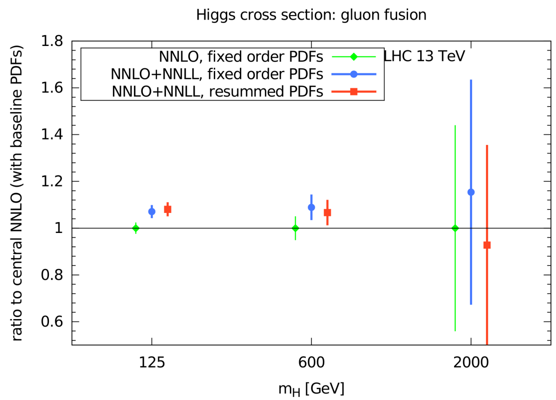
- THRESHOLD RESUMMATION INCLUDED IN FIT (DIS, DY, TOP DATA)
- EFFECTS NOT NEGLIGIGLE AT NLLO, LARGE x, MORE MODERATE AT NNLO
- EFFECT ON PDFs COMPARABLE TO EFFECT ON MATRIX ELEMENT, ANTICORRELATED TO IT

Bonvini, Marzani, Rojo, Rottoli, Ubiali et al., 2015

SLEPTON PAIR PRODUCTION



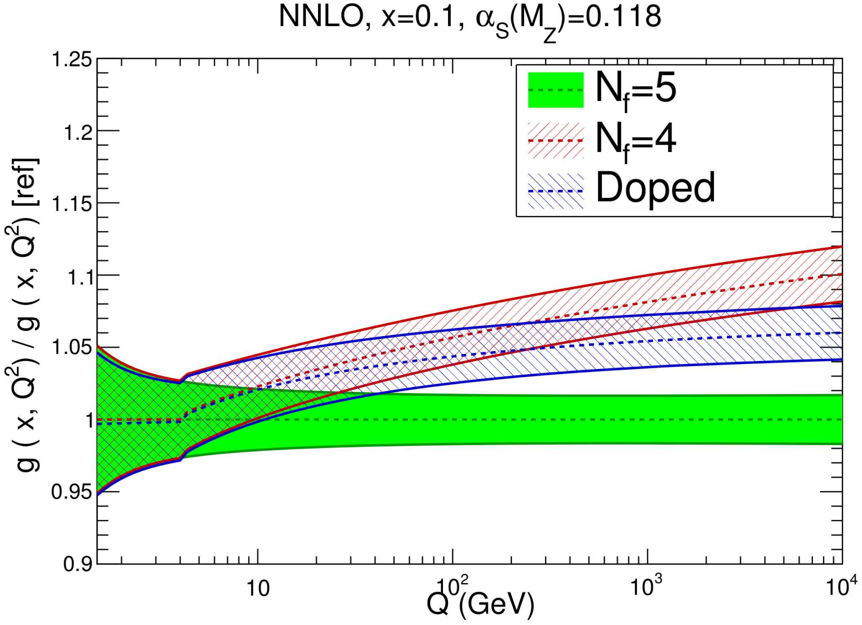
HIGGS IN GLUON FUSION VS m_H



DOPED PDFs

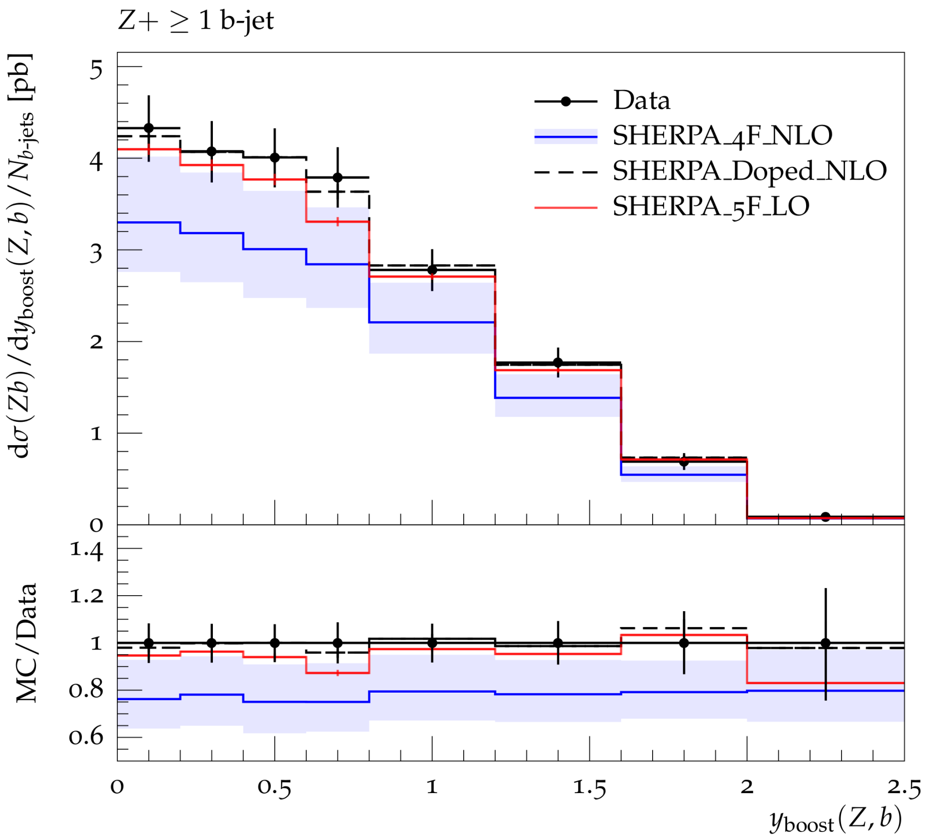
- 4FS α_s IS OFF BY 5% AT THE W MASS $\Rightarrow$ CAN LEAD TO SERIOUS ERROR FOR PROCESSES WHICH START AT HIGH ORDER IN α_s (EG $t\bar{t}b\bar{b}$ PRODUCTION)
- USE "DOPED" PDFs: PDF EVOLVE IN 4FS, ALPHAS RUNS IN 5FS, MUST SUBTRACT MISMATCH (Napoletano, Pozzorini, S.F., 2015)
- $W + b$ p_T SPECTRUM: AGREES WELL WITH DATA WHILE 4FS REPRODUCES SHAPE BUT UNDERSHOOTS NORMALIZATION

GLUON VS Q^2, $x = 0.1$
DOPED VS 4F VS 5F



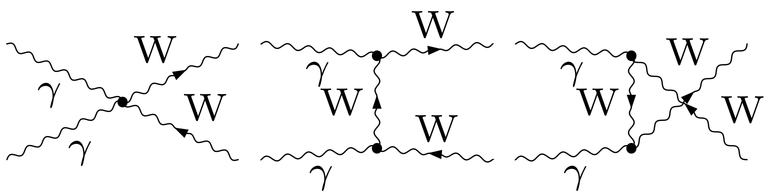
(Bertone, Carrazza, Rojo, 2015)

$Z + b$, p_T SPECTRUM
DOPED VS 4F VS 5F



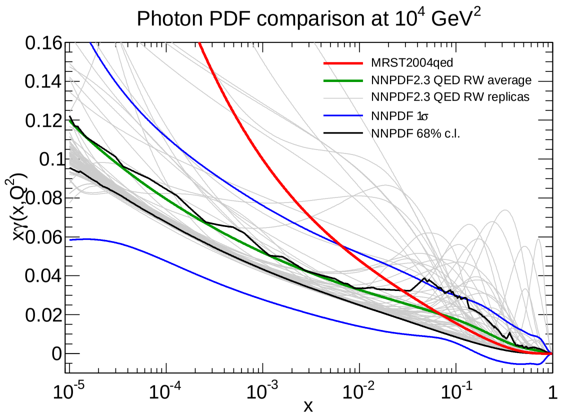
(Napoletano, 2015)

QED PDFs



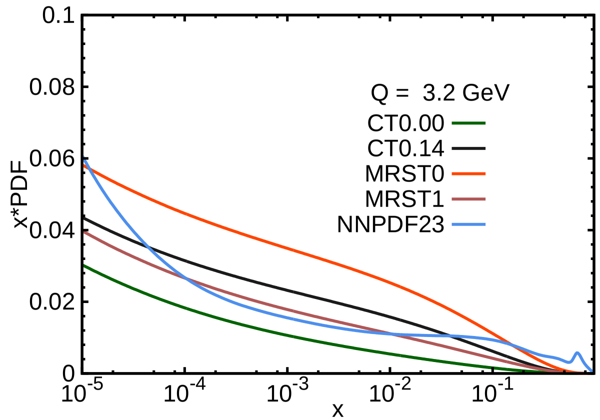
- NNPDF2.3 QED PHOTON PDF DETERMINED FROM FIT
  TO LHCb LOW-MASS DY, ATLAS W PRODUCTION AND HIGH-MASS (Carrazza et al. 2013)
- PREVIOUS MRST2004QED (MODEL); RECENT CT14QED
  (MODEL+ CONSTRAINTS FROM ISOLATED PHOTON IN DIS FROM HERA) (Schmidt, Pumplin, Stump, Yuan, 2015)
- PHOTON COUPLES DIRECTLY TO W
- PHOTON-INDUCED W PAIR PRODUCTION
  COMPARABLE TO QUARK-INDUCED FOR LARGE INVARIANT MASS

γ: NNPDF2.3QED VS MRST2004



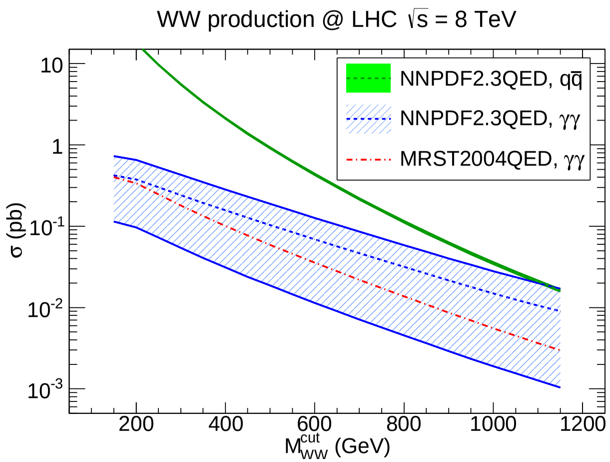
NNPDF2.3QED

γ: NNPDF2.3QED VS MRST2004 VS CT14QED



CT14QED

W PAIR PRODN.: $\bar{q}q$ VS $\gamma\gamma$



(NNPDF2.3QED)

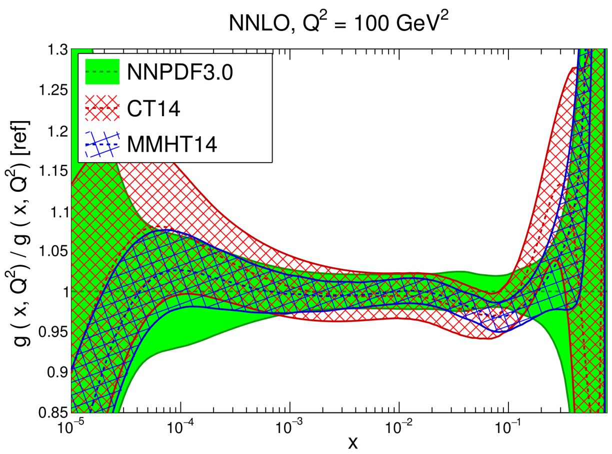
RUN II AND BEYOND

PDFS AT LHC RUN II

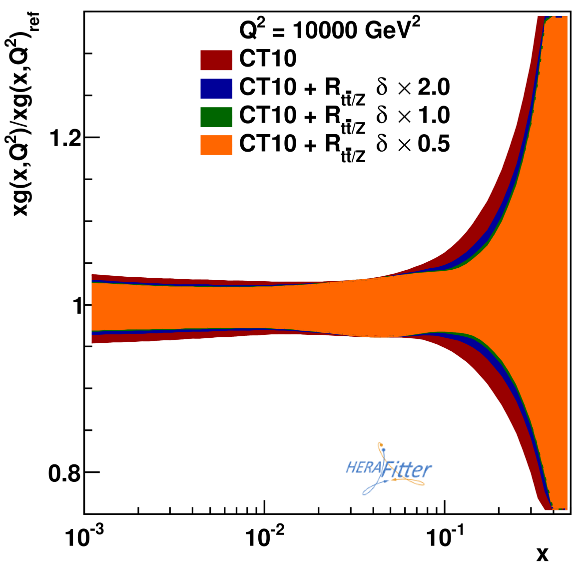
- DATA AT HIGHER CM ENERGY & INFO ON CORRELATION TO LOW ENERGY
  $\rightarrow$ EXTENDED KINEMATIC COVERAGE & REDUCED SYSTEMATICS
- POSSIBLY REDUCED STAT. UNCERTAINTIES
- EXPECT REDUCTION IN MODEL DEPENDENCE
- MODERATE REDUCTION IN UNCERTAINTY
- FURTHER IMPROVEMENTS DUE TO THEORY
  EXAMPLE: GLUON FROM NNLO Z p_T DISTRIBUTION

THE GLUON

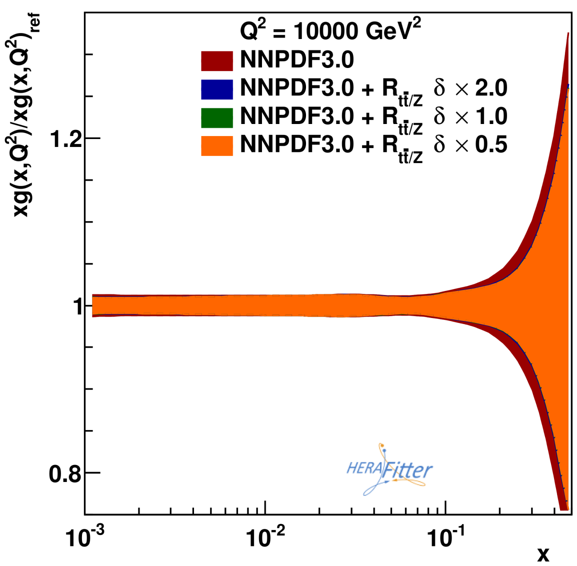
NOW



CTEQ AFTER RUN II



NNPDF AFTER RUN II



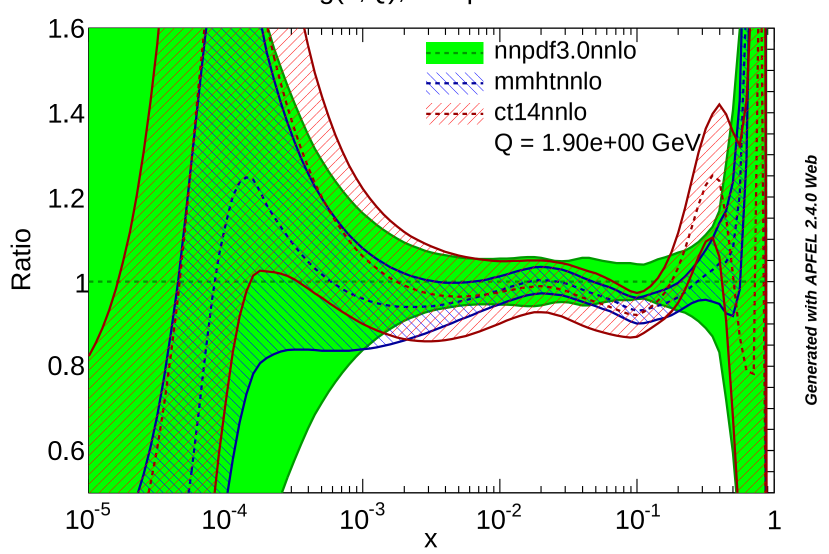
(PDF4LHC: 1507.00556)

PDFS AT THE LHEC?

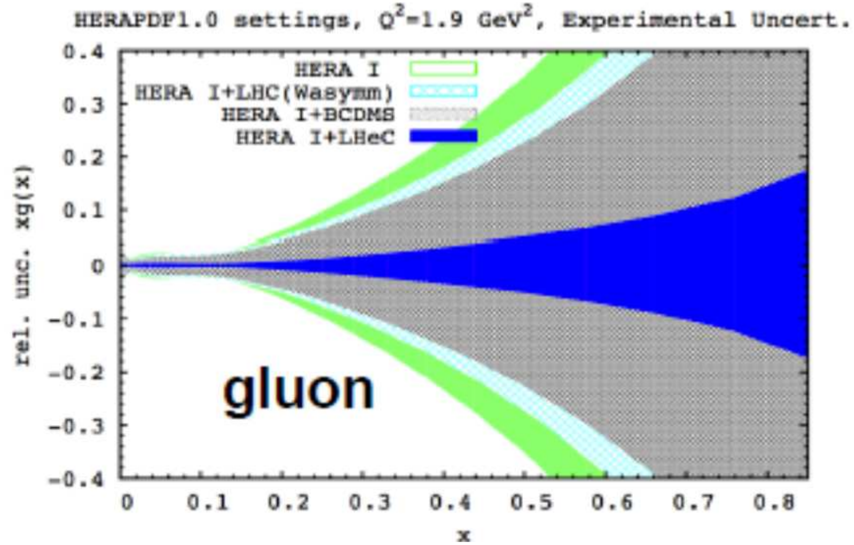
- ESPECIALLY IF CORRELATION INFO AVAILABLE, LHC RUN II CAN LIKELY
  - REMOVE SYSTEMATIC BIAS & DISCREPANCIES
  - BRING DOWN PDF UNCERTAINTIES TO $\sim 4\%$ LEVEL
- VERY DIFFICULT TO REDUCE UNCERTAINTIES FURTHER AT A HADRON COLLIDER
- HIGH-ENERGY DEEP-INELASTIC DATA COULD LEAD TO PDFS AT 1% LEVEL

THE GLUON AGAIN

NOW



AT THE LHEC



(A. Cooper-Sarkar & Voica Radescu, 2015)

SUMMARY

- PDFs determined from largest dataset agree well
- theoretical uncertainties and the inclusion of theory effects is the next frontier
- LHC-Run II likely to trigger more methdological improvements, but lead to moderately improved uncertainties

APOLOGIES for not covering many developments:

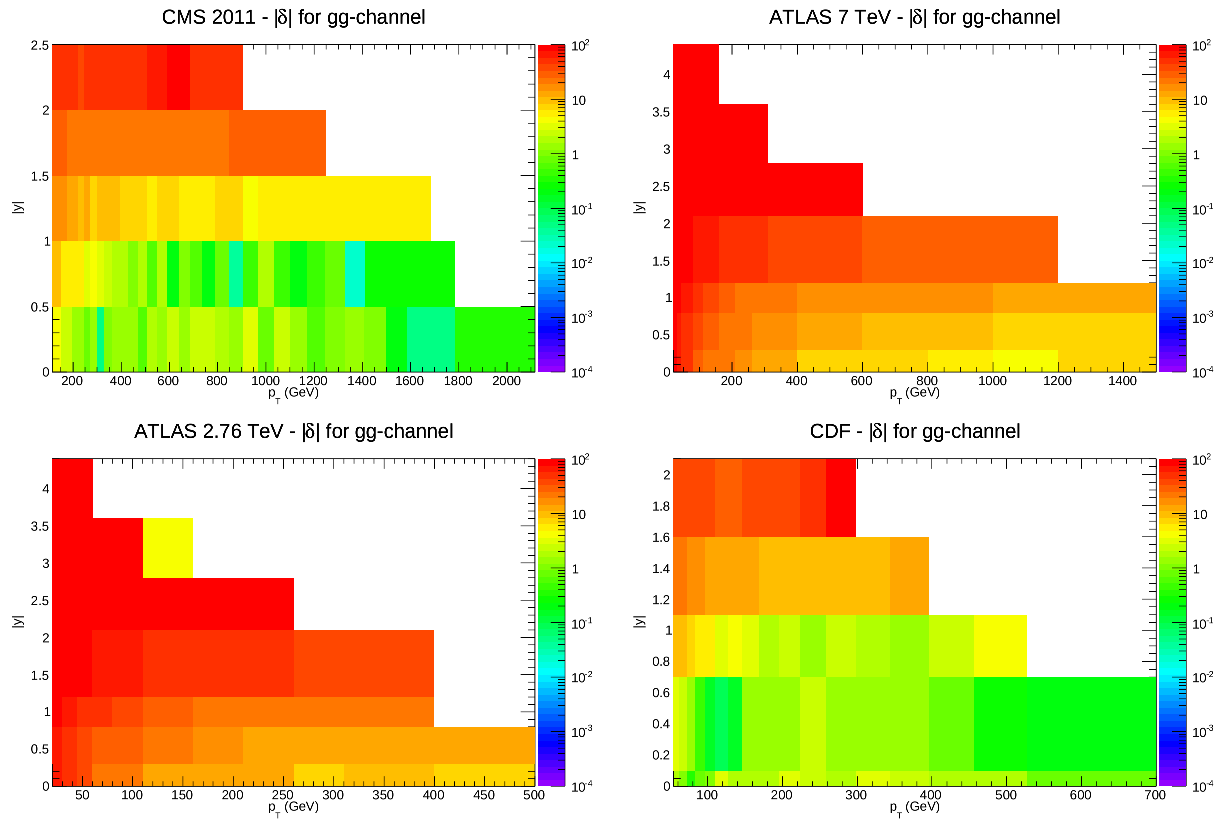
- α_s and HQ masses from PDF fits
- higher twists and nuclear corrections
- nuclear PDFs
- polarized PDFS
- ...

PDFs ARE NOT PLUMBING!

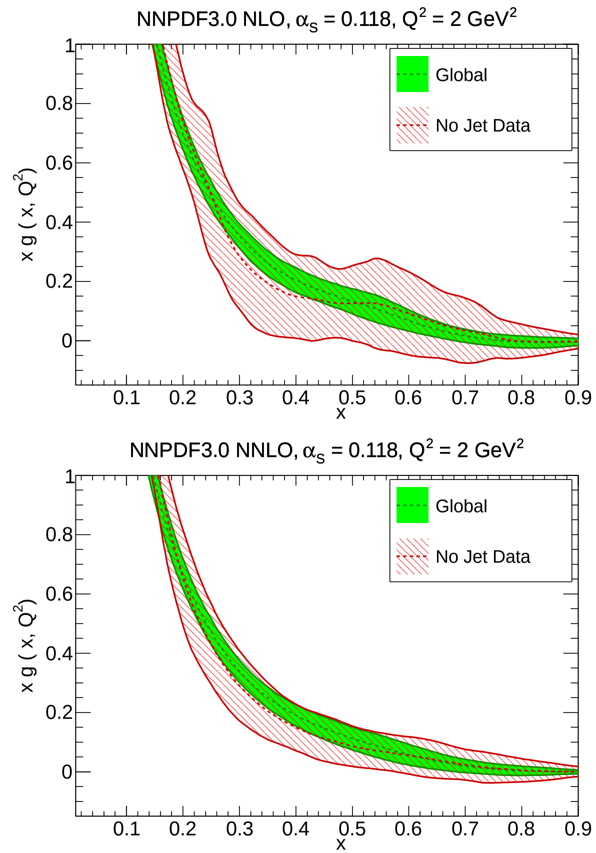
EXTRAS

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

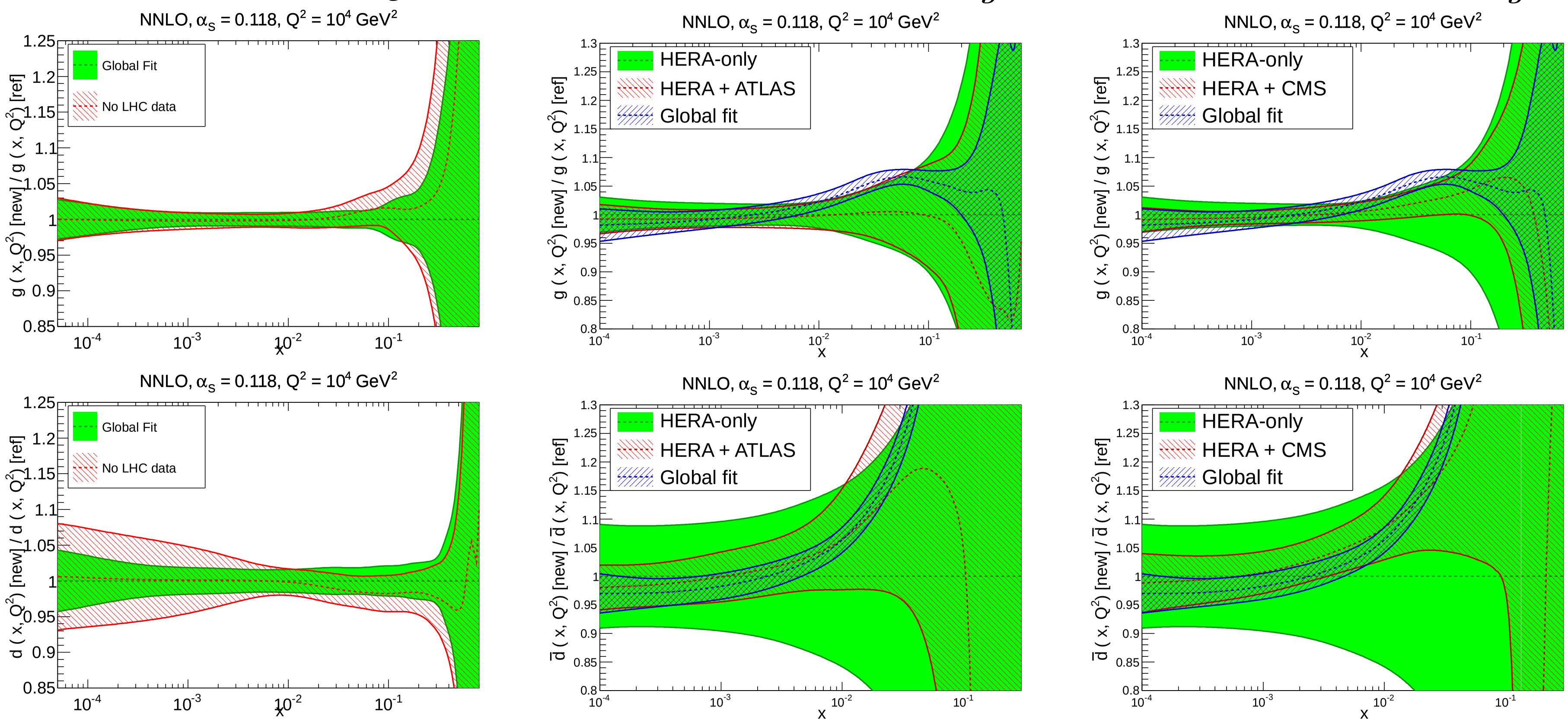
THE IMPACT OF LHC (AND HERA) DATA

- 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& $\bar{d}$

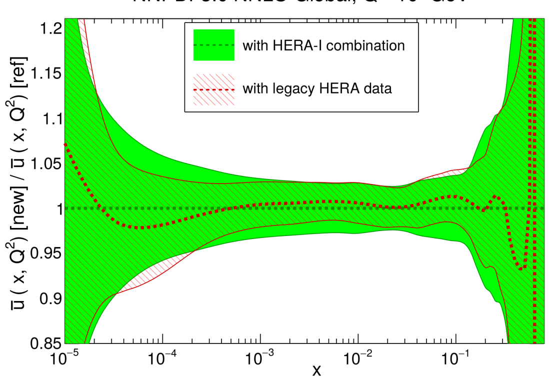


IMPACT OF THE COMBINED HERA DATA

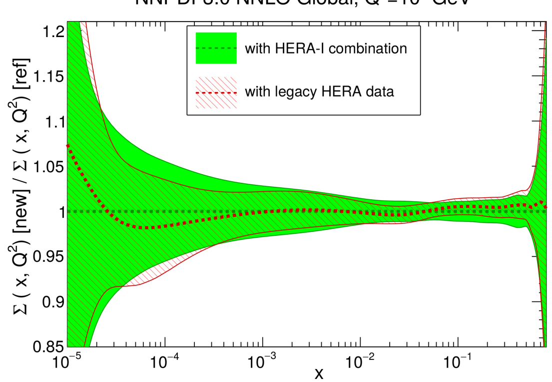
- REMOVE ALL HERA-II DATA FROM NNPDF3.0 FIT
- REPLACE COMBINED HERA-I+ SEPARATE ZEUS, H1 DATA WITH COMBINED HERA I+II IN NNPDF3.0

GLOBAL FIT WITH ONLY HERA I VS COMBINED HERA I+II

ANTIUP

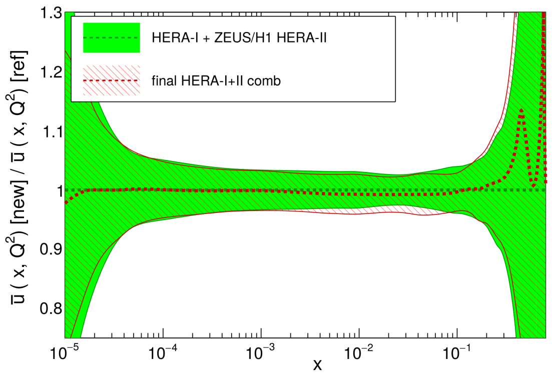


QUARK SINGLET

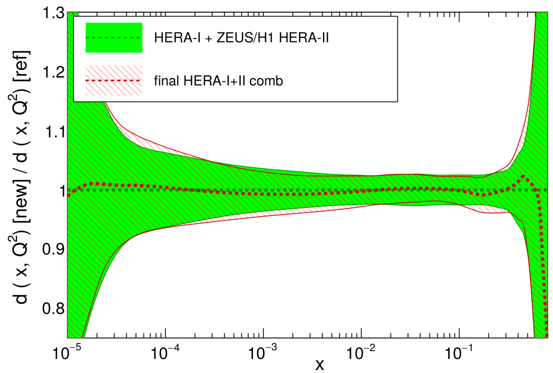


GLOBAL FIT WITH HERA I+UNCOMBINED HERA II VS COMBINED HERA I+II

ANTIUP



DOWN



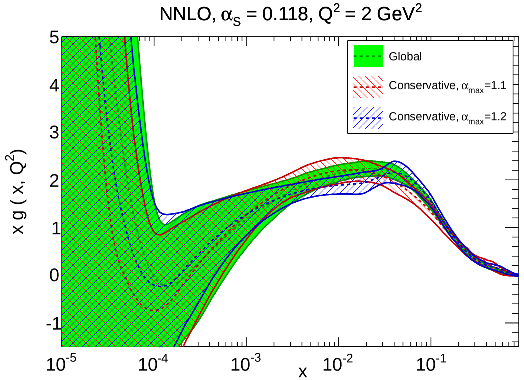
- IMPACT OF HERA-II ON GLOBAL FIT MODERATE
- DIFFERENCE BETWEEN COMBINED & UNCOMBINED EXTREMELY SMALL

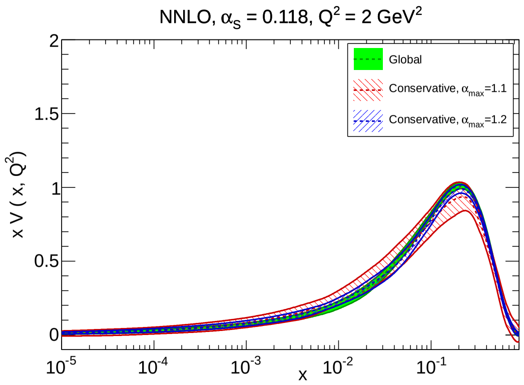
CONSERVATIVE PARTONS

- 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



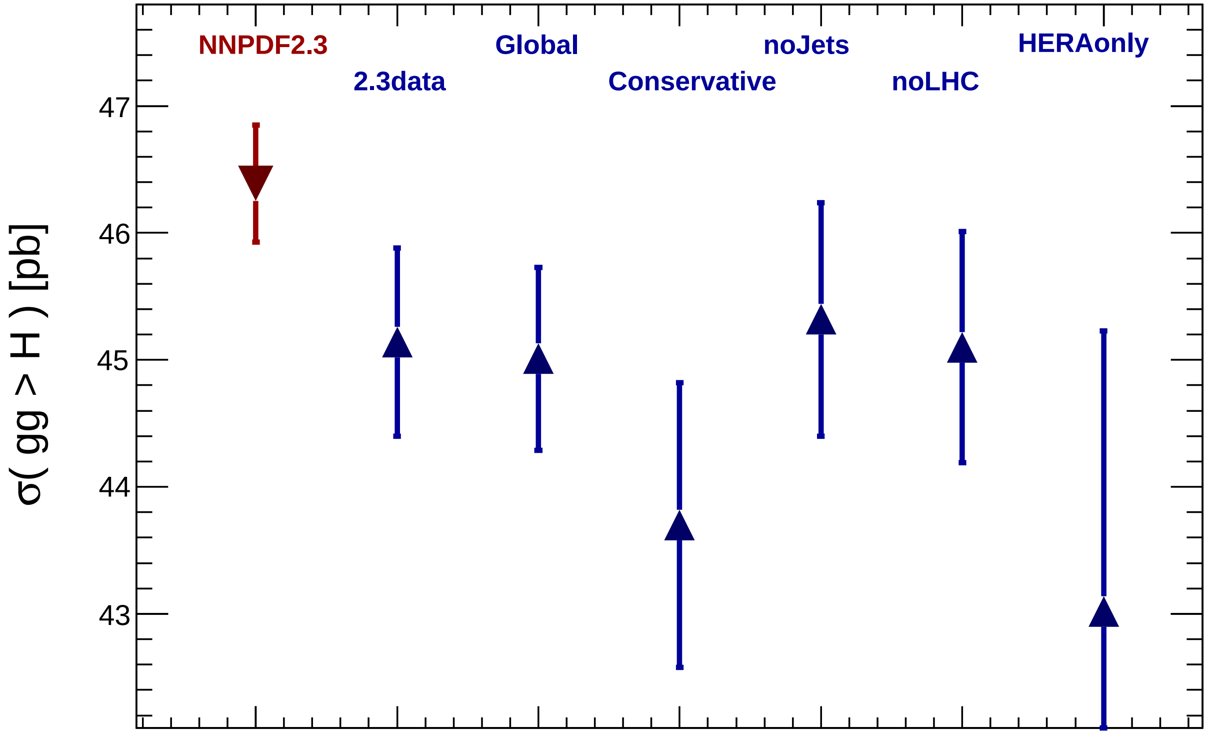


α PEAK FOR EXPERIMENTS DISCARDED IN CONS. FIT WHEN INCLUDED OR EXCLUDED FROM FIT

	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

IMPACT OF INDIVIDUAL DATASETS
HIGGS IN GLUON FUSION

NNPDF3.0 NNLO, LHC 13 TeV, iHixs1.3.3, α_S=0.118



REQUIREMENTS FOR INCLUSION

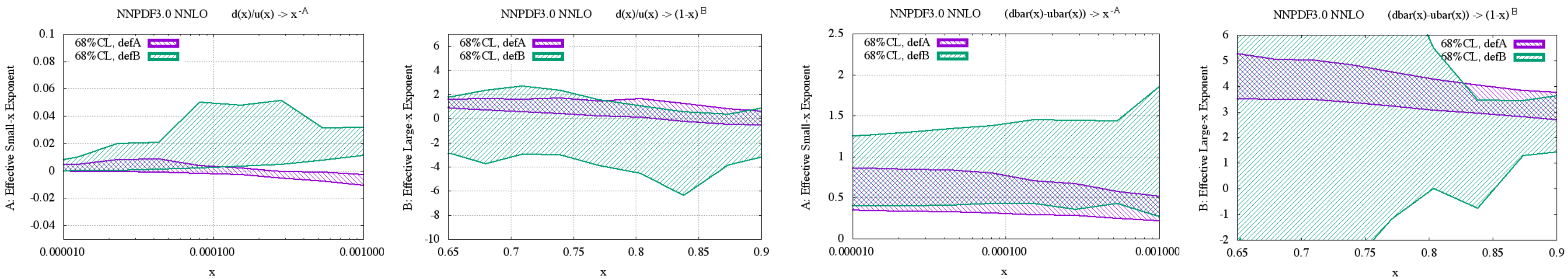
PDFs TO BE INCLUDED IN THE COMBINATION MUST SATISFY REQUIREMENTS WHICH MAKE THEM COMPATIBLE
DOCUMENT IN PDF4LHC APRIL 2015 INDICO
SOME LISTED HERE (SEE DOCUMENT FOR FULL LIST):

- 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)

ASYMPTOTIC EXPONENTS

- IN NNPDF APPROACH, PDF BEHAVIOUR DETERMINED BY DATA
- AS $x \to 0$, PDF GOES AS $x^{-\alpha}$, AS $x \to 1$, PDF GOES AS $(1-x)^{\beta}$
- DEFINE EFFECTIVE EXPONENTS $\alpha \equiv -\frac{\ln f_i(x)}{\ln 1/x}$, $\beta \equiv \frac{\ln f_i(x)}{\ln(1-x)}$ (DEF A)
  OR $\alpha \equiv \frac{d}{d\ln x} \ln f$, $\beta \equiv \frac{d}{d\ln(1-x)} \ln f$

$d/u\ \alpha$ | $d/u\ \beta$ | $\bar{d}-\bar{u}\ \alpha$ | $\bar{d}-\bar{u}\ \beta$

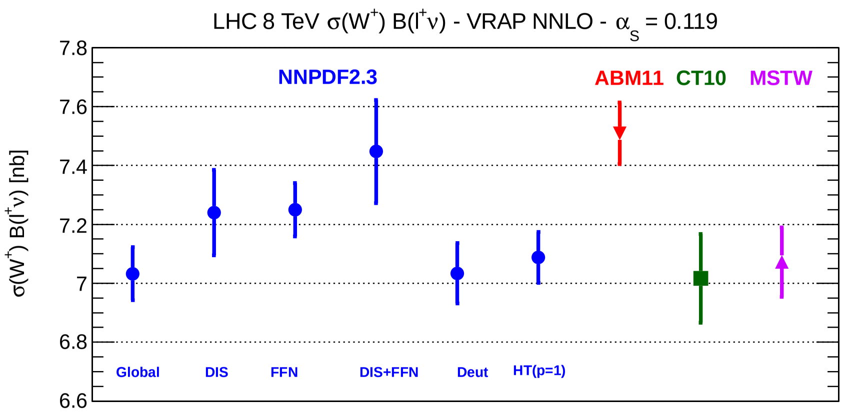


- d/u: $\alpha \sim 0$ TO GOOD APPROX; $-1 \lesssim \beta \lesssim 2$
- $\bar{d}-\bar{u}$: $0.5 \lesssim \alpha \lesssim 1.5$ (REGGE: 0.5); $3.5 \lesssim \beta \lesssim 4.5$
- REGGE BEHAVIOUR AT SMALL x SUPPORTED BY DATA,
  COUNTING RULES CANNOT BE VERIFIED ACCURATELY

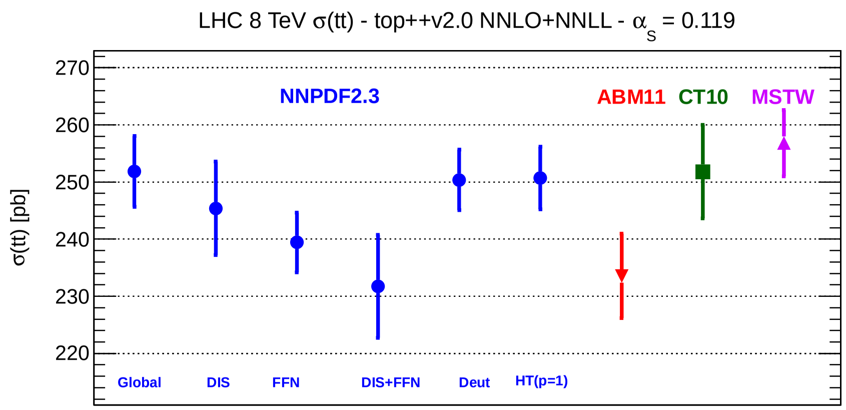
FFN PDFs

- SOME PDF SETS ADOPT A FFN SCHEME (ABM, JR)
- ABM ALSO INCLUDES HIGHER TWIST & NUCLEAR CORRECTIONS
- ALSO, ABM MOSTLY BASED ON DIS DATA
  (ONLY HADRONIC DATA IS ITEMIZE FIXED-TARGET DY)
- WHAT IS THE RELATIVE SIZE OF ALL THESE EFFECTS?
- NNPDF WITH FFN &DIS DATA SET AGREES WITH ABM;
  HIGHER TWIST & NUCLEAR CORRRECTIONS HAVE SMALL & LOCALIZED EFFECT;
  SIMILAR RESULTS FOUND BY MSTW AND CTEQ

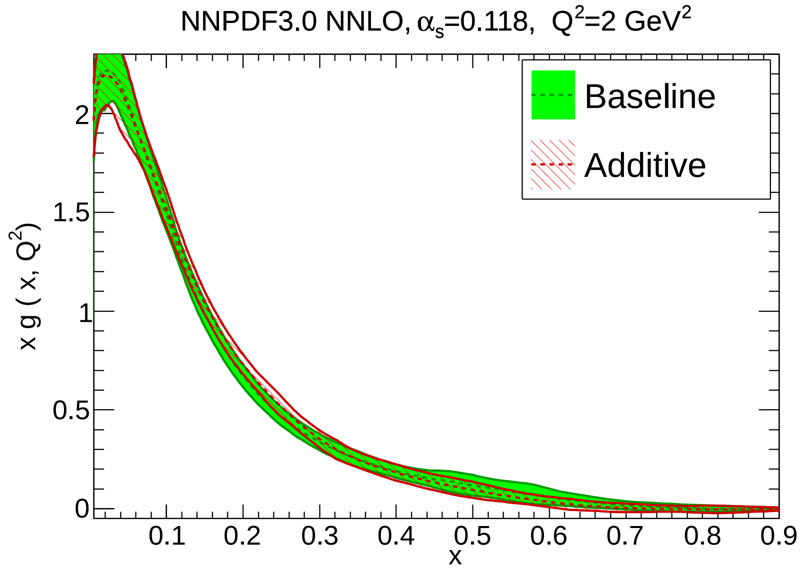
W^+

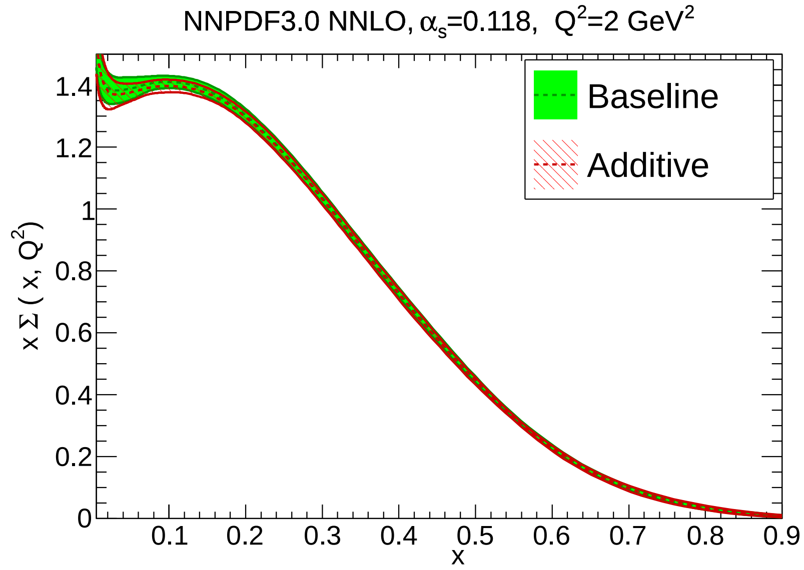


TOP



MULTIPLICATIVE VS. ADDITIVE UNCERTAINTIES





- NORMALIZATION UNCERTAINTY PROPORTIONAL TO MEASURED VALUE $\Rightarrow$ 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

THE VALUE OF α_s

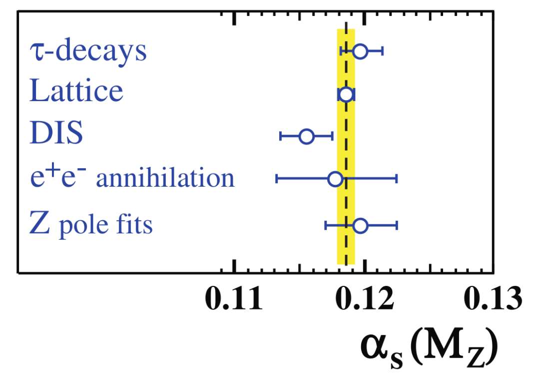
PDG VALUE (AUGUST 2014): $\alpha_s(M_Z) = 0.1185 \pm 0.0006$

- LATTICE UNCERTAINTY CURRENTLY ESTIMATED BY FLAG (arXiv:1310.8555) TO BE TWICE THE PDG VALUE (± 0.0012)
  (IF PDG WERE TO ADOPT THIS, COMBINED UNCERTAINTY LIKELY TO DOUBLE)
- IT IS AN AN AVERAGE OF AVERAGES
- SOME SUB-AVERAGES (E.G. DIS) INCLUDE MUTUALLY INCONSISTENT VALUES
- 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^{3}LO, NO DEP. ON HADRON STRUCTURE) GIVES

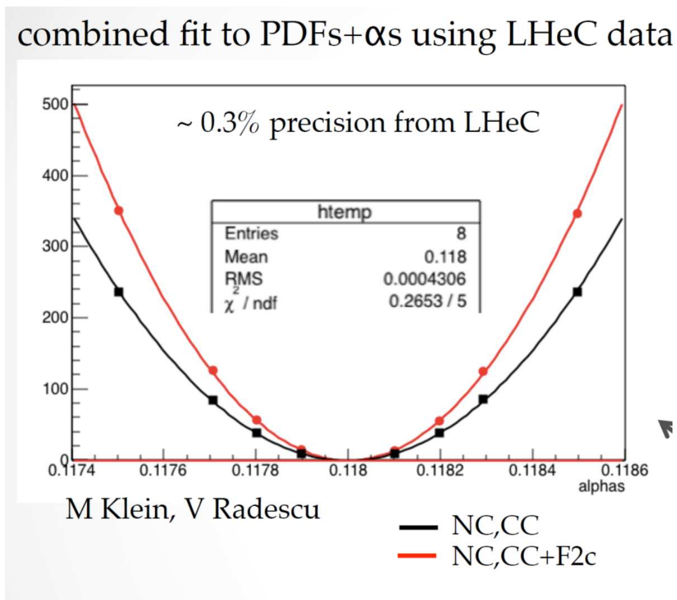
$$\alpha_s = 0.1196 \pm 0.0010$$

- LITTLE PROGRESS FOR MANY YEARS: PDG 1998-2006 $\Delta\alpha_s(M_Z) = 0.002$; PDG 2010-2014 $\Delta\alpha_s(M_Z) = 0.0006 \div 0.0008$ (CHANGE OF AUTHOR)
- UNLIKELY TO CHANGE - SHOULD DETERMINE α_s FROM HIGGS IN GLUON FUSION?

α_s DETERMINATIONS IN PDG



α_s AT THE LHEC



- COULD BE DETERMINED ACCURATELY AT THE LHEC OR AT A NEUTRINO FACTORY!